AGARD-AR-360 Vol. II

AGARD

ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

7 RUE ANCELLE, 92200 NEUILLY-SUR-SEINE, FRANCE

AGARD ADVISORY REPORT 360

Aerospace 2020

(Aéronautique et espace à l'horizon 2020)

Volume II — Main Report

NORTH ATLANTIC TREATY ORGANIZATION

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North Atlantic Treaty Organization
Organisation du Traité de l'Atlantique Nord

The Mission of AGARD

According to its Charter, the mission of AGARD is to bring together the leading personalities of the NATO nations in the fields of science and technology relating to aerospace for the following purposes:

— Recommending effective ways for the member nations to use their research and development capabilities for the common benefit of the NATO community;

— Providing scientific and technical advice and assistance to the Military Committee in the field of aerospace research and development (with particular regard to its military application);

— Continuously stimulating advances in the aerospace sciences relevant to strengthening the common defence posture;

— Improving the co-operation among member nations in aerospace research and development;

— Exchange of scientific and technical information;

— Providing assistance to member nations for the purpose of increasing their scientific and technical potential;

— Rendering scientific and technical assistance, as requested, to other NATO bodies and to member nations in connection with research and development problems in the aerospace field.

The highest authority within AGARD is the National Delegates Board consisting of officially appointed senior representatives from each member nation. The mission of AGARD is carried out through the Panels which are composed of experts appointed by the National Delegates, the Consultant and Exchange Programme and the Aerospace Applications Studies Programme. The results of AGARD work are reported to the member nations and the NATO Authorities through the AGARD series of publications of which this is one.

Participation in AGARD activities is by invitation only and is normally limited to citizens of the NATO nations.

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Foreword

Change is affecting every aspect of our lives, and the pace of change is accelerating. In an effort to forecast where the forces of change will lead NATO and its member Nations over the next quarter century, the NATO Advisory Group for Aerospace Research and Development (AGARD) commissioned the *Aerospace 2020* study.

The study attempts to strike a balance between possibility and promise. Some discussions are undoubtedly too conservative while others too optimistic. In any case, *Aerospace 2020* attempts to identify methods and processess that will help the Alliance and the Nations benefit from the opportunities, and prepare for the possible dangers, which change inevitably creates.

The study involved virtually all of the AGARD organisation, capatalising, in particular, on the strengths of its seven Technical Panels composed of experts in fields ranging from aerospace medicine to fluid dynamics. The study also tapped the military expertise of representatives from AGARD's Aerospace Applications Studies Committee and the information management skills of the Technical Information Committee. Consistent with the nature and philosophy of AGARD, each of these participants expanded the network of professionals to include views and opinions of civilian and military experts from industry, government and academia.

We wish to take this opportunity to thank all of the people who contributed to the *Aerospace 2020* study and assisted in its preparation and production. Special thanks are extended to Dr. Hywel Davies, rapporteur; to Lt. Col. John Wheatley, study executive; and to Jürgen Wild, Director of AGARD, and his staff.

As AGARD evolves into NATO's new Research and Technology Organisation, it will retain its spirit of service to the Alliance, of international cooperation and of dedicated professionalism. It is in keeping with this spirit that *Aerospace 2020* is presented, and we hope the study will prove valuable to NATO and its members as plans, preparations, and decisions are made for our entry into the 21st century.

Avant-propos

Le changement a des répercussions sur tous les aspects de notre vie, et son rythme s'accélère. Afin de prévoir jusqu'où l'OTAN et ses pays membres seront conduits par les forces du changement au cours des prochaines vingt cinq années, le Groupe consultatif pour la recherche et les réalisations aérospatiales de l'OTAN (AGARD) a lancé l'étude "Aéronautique et espace à l'horizon 2020".

L'étude tente de trouver un juste équilibre entre les possibilités et les potentialités. Certains des débats qu'elle contient sont, sans doute, soit trop conservateurs, soit trop optimistes. Quoiqu'il en soit, "Aéronautique et espace à l'horizon 2020" tente d'identifier les méthodes et les processus qui permettront à l'Alliance et aux Nations de profiter des possibilités offertes et de se prémunir contre les dangers potentiels qui sont la conséquence inévitable de tout changement.

L'étude a bénéficié de la participation de la quasi-totalité de la structure AGARD, tout en tirant parti des connaissances de ses propres Panels techniques, composés d'experts dans tous les domaines aéronautiques, allant de la médecine aérospatiale à la dynamique des fluides. L'étude a également fait appel aux compétences techniques militaires des membres du Comité des études en vue d'applications aérospatiales de l'AGARD, ainsi que le savoir faire en gestion de l'information de son Comité d'information technique. Conformément à la nature et à la philosophie de l'AGARD, chacun des participants a cherché à élargir son réseau de professionnels pour y inclure les avis et les opinions d'experts civils et militaires travaillant dans l'industrie, dans l'administration et aux universités.

Nous saisissons cette occasion pour remercier tous ceux qui ont contribué à la réalisation de l'étude "Aéronautique et espace à l'horizon 2020". En particulier, nous tenons à exprimer nos plus vifs remerciements au Docteur Hywel Davies, rapporteur; au Lt. Col. John Wheatley, administrateur responsable de l'étude; et à Jürgen Wild, le Directeur de l'AGARD, et son personnel.

En évoluant vers la nouvelle Organisation OTAN de Recherche et Technologie, l'AGARD continuera à apporter à l'Alliance sa volonté de servir, son esprit de coopération internationale et sa vocation professionnelle. C'est dans cet esprit que l'étude "Aéronautique et espace à l'horizon 2020" est présentée. Nous espérons qu'elle s'avérera utile pour l'OTAN et ses pays membres, pour les plans, les préparatifs et les décisions prises en vue de notre entrée dans le 21ième siècle.

Michael I. Yarymovych
Chairman of AGARD

Nils Holme
Study Director
Aerospace 2020

La version française de ce volume paraîtra ultérieurement

Contents

1. INTRODUCTION

The challenge of change which NATO is facing has many dimensions, one of which is the rapid advance of technology. The changes are such that their combined effects have the potential to significantly affect the quality of military strength in the future.

The NATO Advisory Group on Aerospace Research and Development (AGARD) recognised that these changes and their ramifications are of such importance that they should be examined more thoroughly. In March 1995, AGARD's National Delegates Board commissioned a study with the following objectives:

- To assess how emerging technologies may influence changes in aerospace systems and concepts of operation;
- To alert decision makers to the advantages the emerging technologies may have for NATO and NATO Nations, and to make them aware of the possible threats that new and readily available technologies may pose when acquired by potential adversaries;
- To recommend to the Nations active pursuit, both individually and cooperatively, of the most promising aerospace technologies and to offer advice, where appropriate, on collective action.

To achieve these objectives, *Aerospace 2020* explores the most advanced technologies being researched and developed in laboratories today. Rather than speculate on science and technology theories for the future, the study focuses on the most promising current technologies and the organisational and tactical consequences they will have at the field and system levels over the course of the next twenty-five years.

The scope of the study - from 1995 to the year 2020 - supports the view, held by many, that all major systems which will be deployed in ten years exist today. After ten years, however, new systems may lead to radically new concepts in the way military force, or the threat of its use, is employed to influence the wills and actions of others. It has been noted that "20/20" vision is the medical designation for unimpaired eyesight, and it is often said that "hindsight is always 20/20". It is AGARD's hope that this study of aerospace technology and the effects it will have, as we approach the year 2020, will prove to have been a clear vision with 20/20 foresight.

1.1 Basic Assumptions

The primary purpose of the Alliance is to provide military security for its member Nations. This and the following assumptions form the foundation upon which discussions presented in this volume are based:

- NATO must remain prepared to act in direct defence of its member states;
- NATO must remain prepared to take action against threats to vital interests of the Alliance outside the NATO area. Such operations may range from large-scale war to low-intensity conflicts to counter-terrorist activity;
- Ethical constraints that exist within NATO regarding the conduct of violent conflict and warfare will not diminish and, in fact, are likely to increase. Potential opponents, however, may not respect or practice the same constraints;
- NATO membership will expand in the coming decades. This expansion will require the integration of new national forces and infrastructures.

In addition to remaining a strong and independent alliance, NATO will continue to work closely with the United Nations in its efforts to resolve international conflicts by diplomatic and/or military means. The UN will continue to support military forces involved in a number of operations around the world. As today, NATO may serve as the primary contractor, with operations conducted under full NATO command, or as a contributor to forces under UN command.

To meet its obligations, UN forces must be capable of rapid, flexible deployment. NATO is the only organisation with the ability to efficiently run a multinational operation. It is essential to world peace and stability that this ability be maintained and improved. For NATO, however, conducting non-traditional missions, possibly

with non-NATO Nations that do not necessarily share the same approach to technology, organisation, or command and control methods, will pose a continuing challenge in the years to come.

1.2 Approach

Aerospace 2020 is the result of joint efforts by the AGARD Technical Panels and the Aerospace Applications Studies Committee (AASC). Beginning in 1995 and ending in early 1997, a study group, consisting of representatives from the AGARD Panels and the AASC, a study director, a rapporteur, and a study executive, coordinated the work, selected the main topics of the study, and reviewed the results. This collaborative approach permitted the study group to draw on the insights of the large number of internationally established experts who form the membership of these bodies. However, this approach also limited the scope of the study to the areas of expertise covered by the AGARD bodies.

The first step of the study was a "bottom-up" survey conducted by the AGARD Technical Panels to determine what their experts thought would be the most significant changes in aerospace technology over the next 25 years. Following a review from the military point of view by the AASC, a list of topics was defined. Two non-technical discussions - "The Future of Defence Environments" and "Enduring Military Needs" - were coordinated by the AASC. Discussions of other topics selected for inclusion were coordinated by the appropriate AGARD Technical Panel, as shown in Table 1-1.

Aerospace 2020 consists of three parts: Volume One - a brief summary of the main results of the study, with recommendations; Volume Two - a detailed discussion reflecting the topics selected for study, organised in a way that enables review of their interrelationships and impact; Volume Three - a series of short technical papers, selected for their specialist interest and carrying the signatures of their authors or the contributing AGARD Technical Panel. A list of study group members is provided in *Aerospace 2020, Volume 1, Appendix A.*

A detailed list of the AGARD membership during the study, along with other contributors, is provided in Appendix A of this volume.

AGARD Technical Panel:	Topic:
Aerospace Medical Panel (AMP):	Human and Machine Interaction Human Implications of Sustained Operations
Flight Vehicle Integration Panel (FVP):	Aircraft Design Integration Synthetic Environments
Fluid Dynamics Panel (FDP):	Extreme Long-Range Vehicles Versatile Access to Space
Mission Systems Panel (MSP):	Mission Management Unmanned Tactical Aircraft
Propulsion and Energetics Panel (PEP):	Hypersonic Air-Breathing Missiles
Sensor and Propagation Panel (SPP):	Communications Electronic Warfare Progress in Stealth Versus Anti-Stealth Real-Time Reconnaissance, Surveillance, and Target Acquisition (RSTA)
Structures and Materials Panel (SMP):	Affordability

Table 1-1: Panel Contributions by Topic

1.3 From Technology to Operational Capabilities

As mentioned above, one of the aims of the *Aerospace 2020* study is to assess the way in which emerging technologies may influence changes in aerospace systems and concepts of operation. Projections of technological capabilities are somewhat uncertain, but most of these uncertainties are well understood. This is not always the case when making projections of operational capabilities that result from advances in technology, especially when such projections involve totally new systems and operational concepts. New concepts sometimes encounter secondary limitations, for example in methods or basic principles, which significantly affect their implementation. These factors are discussed in some cases in the study, but limitations may also be recognised in the future that are not understood today.

It is also important to acknowledge that assessments of concepts of operation are limited and, to a great extent, are based on qualitative analysis. The AGARD Technical Panels are primarily technology oriented, dealing at the systems level only in the fields of aircraft and aircraft missions. Systems considerations are more typically examined by AGARD in ad hoc studies initiated by the AASC, generally two per year for selected topics.

1.4 Relationship to Other Studies

Several surveys of emerging military technologies and assessments of their consequences have been published in recent years; most notably *New World Vistas*, produced by the US Air Force Scientific Advisory Board in 1995. This study is of great value, particularly with respect to its completeness and depth of coverage. Of course, specialist judgements will sometimes differ in matters of the more distant future, and there are a few such differences in *Aerospace 2020.*

More significantly, the studies differ in their basic points of reference. NATO's perspective regarding military threats, opportunities, and recommendations is determined by the purposes and functions defined in the North Atlantic Charter. This focus is different from that of the US Air Force.

Thus, *Aerospace 2020* discusses topics relevant to the Alliance or to individual Nations as members of the Alliance. This means, for example, that the study makes no attempt to examine topics from a global perspective. By its very nature, NATO provides a framework for the establishment of common infrastructure systems and common development projects. The *Aerospace 2020* study examines activities which can be undertaken by the Alliance or by member Nations working cooperatively through the Alliance.

2. THE FUTURE DEFENCE ENVIRONMENT

The challenges to security, the options available for defence planning, and the specific consequences of defensive actions are part of the world around us. A study of technological developments and their potential impact must take into consideration the influence of many day-to-day factors that are not technical and are less predictable.

While the basic assumptions about NATO's role through the next 25 years as discussed in Chapter 1 are assumed to be invariable, other assumptions common to the *Aerospace 2020* study are based upon current political, economic, social, and industrial trends that change over the course of time. In general, these factors are well known and widely accepted. They are briefly discussed in the sections of this chapter. In addition, many new factors are identified as a result of the study itself. The influence or potential consequence of a factor is discussed, where it is relevant, in other chapters.

2.1 Causes of Conflict

Although the possibility will remain, it seems unlikely that future conflicts involving NATO will be large-scale wars, where NATO confronts armies of opposing nations or alliances across established international boundaries. It is more likely that NATO forces will be required (or requested) to respond to less structured conflict situations which may arise.

Social Disparity

There is a clear and growing gap between wealthy, developed nations characterised by high per-capital levels of income, consumption of natural resources, and educational achievement, with low birth-rates - and poor nations suffering from high birth-rates and low levels of nearly everything else. These differences are severe today and are expected to continue to increase, escalating in proportion to the population growth in poorer countries.

Internationally, this disparity is a potential source of tension, made worse by differences in national interests and priorities that are increasingly difficult to bridge in the global community. In addition, extreme differences in income and social standards increase the number of refugees and immigrants attempting to move to lands of greater opportunity.

Internally, within the countries having a low standard of living and/or explosive birth-rates, the competition for fixed or shrinking resources is constantly increasing. This adds to the social pressures already created by an inadequate infrastructure and the lack of means to bear the burdens of society. The problems are further compounded by the fact that many of the governments in these countries seem more concerned about maintaining their positions of power and protecting their leadership than they are about improving the social conditions of their people.

All of these factors combine to generate unrest and discontent in environments that, already today, can be characterised as unstable and potentially volatile.

Ethnic and Religious Rivalry

In many cases, ethnic bonds and religious loyalties are becoming stronger and more important than national allegiances. Numerous examples, including the former Yugoslavia, Rwanda, Somalia, and Kurdish activity in the Middle East, clearly suggest that violent conflicts in the future will be quite unlike traditional models, where nations fought nations.

Religious Fundamentalism

Religious fundamentalism - when it causes believers in one religion to be intolerant of believers in any other - is also an increasing source of tension within and between countries. Dangerous friction and tensions may be created internally and internationally when an intolerant and inflexible religious leadership dominates a government and its institutions, and seeks to eliminate all opposition.

Organised Crime

Until recently, drug cartels and crime organisations have remained outside the scope of interest of most Western military forces.

Today, however, drug cartels exert great influence and power in some non-NATO countries, and in others, various organised crime syndicates have created an unofficial economy by enticing government officials to protect business concerns. In the next century, organised crime in some nations may wield as much power and influence as the official government. At the very least, such groups pose a threat to confidentiality and security for the countries where they are entrenched and for the nations attempting to work with these countries.

Terrorism

Historically, in conflict situations, an adversary is deterred from taking some types of action because they understand that an attack against a certain territory, people, or property will have unacceptable consequences for the attacker. In many cases today, however, the attacker considers everything to be acceptable in his view. For some terrorists, for example, intentional self-destruction is sometimes seen as enhancing the cause, rather than detracting from it; a consequence generally not viewed in the same way in Western societies.

Countering terrorism is complicated by the fact that the time, location, and means of an attack may be unpredictable, and the perpetrator(s) unknown. Responding to an attack is equally difficult, because such organisations often do not present a recognisable target afterwards, and determining how, where, when, and against whom a response should be directed is often very difficult.

2.2 Potential threats

The nature of the threats posed, for whatever reasons, by adversaries in the future may well be based on our own military technological advances, as equipment and information once expensive and secure becomes more available commercially, more susceptible to intrusion, and more available covertly.

Civilian Services

Many services important to military operations and previously handled only by expensive military-specific systems and organisations are available today in the civilian market at little or no cost.

Although some of these facilities are not necessarily adequate by NATO standards for NATO operations, they are often sufficient for potential adversaries to use effectively. Communication services, ranging from telephone networks to the Internet and other data transmission services, are readily available for nominal subscription fees and provide such instant connectivity that a potential enemy can coordinate activities world-wide simply by placing a standard telephone call.

Among other things, the Internet gives up-to-date weather information, which is vital for planning and conducting military operations. Very detailed maps for developed countries are available in digital form on CD-ROMs. These maps include details about the infrastructure and other man-made fixed objects with an accuracy of perhaps two metres; this means that it is possible to buy, in the open market, target data needed to engage precision weapons.

Determining position coordinates (position fixing) is now quickly and easily done by using inexpensive, commercially available receivers and the Global Positioning System (GPS). Originally developed at great expense by and for the military, the service is now universally available at no cost to the user. GPS receivers are so cheap that they are a built-in feature on some mobile telephones, standard navigation equipment on small boats, and considered safety devices by many public transport systems, which use them to check the locations of buses and taxis.

Commercial Technology

Similarly, specialised technology and equipment previously developed and controlled by the military are becoming increasingly available, quite literally, off-the-shelf in the civilian market. More powerful and compact computer systems and commercially available electronic components can be assembled into high-quality systems for military use. Ready access to items such as signal processing components and units or precision navigation equipment makes it possible to engage in many advanced projects that once would have been financially prohibitive for potential adversaries without a broad basis of military technology. Although not as sophisticated as some specialised military solutions, commercially available parts, units, and materials are cost effective, efficient, and very capable of supporting significant threats.

While the commercial availability of a variety of suitably advanced subsystems benefits NATO itself by reducing costs, it also means greater competition in the market from countries which previously could not afford to develop or produce such systems.

Accessibility of Military Expertise

As a result of industrial restructuring in the West and, most notably, in countries formerly members of the Warsaw Pact, many military specialists are unemployed, and their expertise is for sale. In addition, a full range of equipment - from weapons systems to aircraft - can be bought cheaply and conveniently on the international arms market. While this may be a temporary phenomenon associated with major political changes in the last decade of the 20th century, skills, knowledge, and expertise that can be used against us are widely available now, and will be for some time to come.

In addition, shrinking Western markets for military expertise and technology may lead industries to pressure governments for more liberal export controls. Such liberalisation could significantly increase the likelihood that our own technology would be used against us in a conflict situation.

Vulnerability of Information

The Internet is, indeed, an "information highway" that makes vast amounts of scientific, technical, and administrative data quickly and easily available to any user anywhere in the world. Not only can information be obtained anonymously, it can also be manipulated, deliberately destroyed, or generated and reproduced in such volume that entire systems are rendered useless. With or without the Internet, sophisticated computer users can enter systems thought to be secure and, with little time or effort, access data, introduce a virus, or corrupt the data and virtually incapacitate or control anyone or anything dependent on the information or the system. It is estimated, for example, that large amounts of money are already being stolen by on-line transactions made via unauthorised entry into banking systems or use of credit card numbers. Ultimately, terrorist groups and individuals, perhaps even dishonest governments, could use similar methods to finance their goals of violent aggression.

2.3 The Nature of the Battlefield

During the next 25 years, the trend to reduce force structures within NATO will continue. Up to now, these reductions have been implemented without significantly enhancing or upgrading individual unit or weapon-systems capabilities. However, improvements will be essential in the future, in view of the demands and uncertainties posed by the wide variety of possible conflict situations and the even wider variety of possible threats created by the easy availability of sophisticated weapons.

The proliferation of advanced technology, high-precision weapon systems, sophisticated sensors and information processing systems, and the threat inherent in the existence of weapons of mass destruction will make the future operating environment for NATO forces much more lethal than in the past. In addition, improved battlefield awareness will make it nearly impossible to amass forces without risking detection and attack. Rapid decision making and execution by commanders at all levels and by all military personnel involved, high mobility, and the pre-emption of enemy actions will be critical to any NATO operation.

Weapon Effectiveness

Each new generation of military technology brings with it the potential to substantially increase the number of battlefield casualties. While the weapons of mass destruction are at the most extreme end of this spectrum, conventional weapons themselves continue to become more lethal. It is now possible for a single fighter aircraft carrying four precision-guided bombs to inflict the same amount of damage to intended targets that once required full bomber squadrons. Once attacked, the risk of military forces being destroyed on the battlefield has increased multi-fold.

Several implications flow from the reality that conventional weapons are becoming more lethal. First, nations and forces will put a higher premium on protecting their assets, including both active and passive means of self-protection. While there may be little that can be done to reduce the effects of a munition once it hits the target, the chances of being attacked can be minimised. Greater priority will be given to preventing or frustrating the detection, targeting, and guidance of munitions, so that weapons are not released, or

are denied vital information that would enable them to move to the impact point once they are launched.

The lethality of the battle space will also encourage the further development of long-range, precision systems that keep their operators as far away as possible from the intended target. This, in turn, will increase the need for and role of unmanned systems in all aspects of combat, from sensors, to smart weapons, to launch platforms for smart munitions. While the cost of such systems could be high, the continued use of manned systems could, in many situations, result in unacceptable - and unsustainable - battlefield losses.

Reaction Times in the Application of Force

The ability to react quickly during the beginning of a conflict could be a major advantage for technologically advanced societies attacked by enemies using highly effective offensive weapons. Achieving this advantage, however, will require strategic and tactical intelligence systems offering a broader range of options than those currently available. Combat operations will need to be even more carefully synchronised than today to enable simultaneous attacks across axes and from various platforms. In short, everything will be happening at a much higher tempo, and the time available for analysis and response will be greatly reduced.

Cost Advantages - Offensive versus Defensive

Advances in weapons technology, in particular the advent of long-range precision weapons and improvements in reconnaissance, surveillance, and target acquisition systems, have reduced the cost of destroying targets relative to the cost of defending against attack.

Furthermore, the high precision and effectiveness of individual weapons have increased the potential gains from attacking first. Although offensive strategies will thus be more cost-effective in the years to come, NATO will remain a defensive alliance. To reduce its vulnerability to attack, it must develop new defensive approaches and, to minimise the risks of surprise, it must take full advantage of technologies for improved situation awareness.

2.4 Keeping NATO Armed and Equipped

The economic and industrial foundations upon which a strong NATO defence is based are in the midst of radical change as the 20th century comes to an end. Significant changes in the international political environment have resulted in reduced defence spending in virtually all NATO Nations and, in turn, reduced markets for existing products, as well as for those in the research and development phase.

The nature of these changes today is well understood, but the challenges or consequences they pose for the next 25 years are uncertain. It is clear, however, that regardless of the current strength or durability of these trends, the way in which NATO is armed and equipped in the future will not be the same as in the past.

The Military Balance Sheet

In response to the new strategic situation, most NATO Nations, and in particular the major Nations, are reducing both their defence forces and their defence budgets. At this point, there has not been a corresponding reduction in operating costs because, in and of itself, the logistical task of reducing and restructuring the forces takes time and resources. As a result, budgets for procurement and for research and development (R&D) have been reduced at a greater rate than the total defence budgets.

In general, leading Nations are maintaining critical R&D programs and reducing the rate of procurements quite drastically. Eventually, however, there will be a better balance in these areas and between expenses and operating costs. Two major challenges in the years to come will be to prevent the elimination of categories of specialised and essential military systems (weapons, weapon carriers, et cetera) and to prevent the loss of industrial capabilities vital to their production and supply.

Industrial Internationalisation

Faced with reductions in national defence budgets, industry is attempting to adjust its capacity to drastically shrinking markets. One approach currently being taken is consolidation within and across national borders. As a result,

the industrial restructuring process is also becoming an internationalisation process, which has direct implications for NATO and the governments of its member Nations.

Since military technology and an armament base are essential to national security and security policy, nations will seek to maintain and ensure access to the technology and industries that supply the systems required. However, the extent to which governments will attempt to influence or control mergers and reorganisation in the years to come is not known.

Reduced budgets also make it more urgent for governments to seek partners and share costs, whether for research and development of large programs or for procurement of expensive and sophisticated military systems. Maintaining access to critical technology will remain a factor in this connection also.

Changes in Defence Production

Current reductions in defence spending are already resulting in less frequent new-product starts, smaller production runs, and rising development costs (especially in proportion to production). In an effort to remain competitive, specialised military and aerospace industries will continue to aggressively reduce costs, and some of these strategies will directly affect NATO Nations.

One strategy, for example, seeks to shorten development cycles and the implementation time of new products. As the number of collaborative projects increases, and as the number of partners within a project also grows, Nations must be prepared to streamline the procedures of cooperation. In the past, cooperative efforts have tended to extend development time and cost. It will be very important to reduce this effect.

The service life of most military systems is much longer than similar systems in the civilian market, where equipment is more often replaced than repaired. As military-specific industries begin to rely more on commercially available parts and products, the already existing problem of maintaining a supply of spare parts will become worse. To ensure the availability of components, NATO is faced with several costly alternatives, including dedicated manufacturing, lifetime purchases of spares, or sub-system redevelopment whenever parts cease to be available.

Ultimately, a shrinking defence industry leads to the loss of skilled and experienced people at all levels. Positions may be eliminated, retirees may not be replaced, or tasks may be assumed by fewer people with a broader range of skills. Longer intervals between projects may result in a loss of continuity and expertise, since skills must be constantly exercised and updated to be maintained. Rapid development times, on the other hand, minimise the amount of expertise that can be shared across program lines.

Competition is the best guardian of efficiency in industry. As industrial restructuring leads to fewer competitors, competition will decrease. Nations must then develop procurement practices with other incentives for efficiency.

3. FUTURE MILITARY NEEDS

Any assessment of technologies for military purposes must have reference to some set of military needs. Statements of current needs reflect the impact of the world situation, and particularly the state of current technology

To assess future technology, an extrapolation from today's needs to the needs of the future is required. Based on the trends outlined in chapter two and on current NATO military guidance[1], the AGARD Aerospace Applications Studies Committee (AASC) developed a view of NATO's military needs in the 2020 time-frame.

Consideration of on-going long-term studies, other available forecasts formulated by member Nations, and NATO forecasts[2] pertaining to future developments of possible opponents, allowed the AASC to extrapolate the enduring aerospace-related requirements of NATO under five major areas of interest:

- Information Exchange and Decision Making,
- Mobility,
- Survivability,
- Mission Effectiveness,
- Sustainability.

In defining these areas of interest, consideration was given to the full spectrum of conflict. While considering the eventuality unlikely, the AASC evaluated the requirements of dealing with a global power threatening NATO interests in the year 2020. The potential for a major conflict as a result of an attack by a regional power or coalition was evaluated, and a variety of more likely scenarios involving NATO forces in operations other than war was considered.

These forecasted needs served as a framework to assess future technology. However, as the future world situation and the path of future technological advance are inherently unpredictable, the needs were considered as a guide, not as a constraint.

[1] Including MC 400, MC 299/4 and Bi-MNC Guidance for Defence Planning.

[2] As presented in MC 161 and MC 164.

3.1 Information Exchange and Decision Making

A fundamental component of success in combat will continue to be the ability to keep the commander's decision cycle shorter than that of the enemy. This allows the commander to seize the initiative, and to bring the right mix and level of force to bear at the right time and place in the battlespace to guarantee victory in the shortest time, with minimal casualties. Effective decision cycles require sufficient information to be extracted quickly from the ever-growing amount of available data, in a usable form for the decision maker. The information flow must be continuous, timely, accurate, and comprehensive, without being overwhelming. Therefore, information will need to be quickly collated and assessed prior to dissemination. Timely dissemination of the decision and the feedback of execution must enable full control and efficient support of force deployment and employment across the entire spectrum of NATO missions.

Because information is essential to command and control of both friendly and hostile forces, all elements of the friendly system must be protected from exploitation or attack. At the same time, innovative means to detect and exploit vulnerabilities of the enemy's system, to include disrupting or destroying capabilities, will become a vital part of NATO's warfighting arsenal.

The essential components of the information system will remain as known today: sensors, information processing, human-machine interface, and communications. The requirements upon these components will be these:

- To deliver 24-hour, all-weather, accurate, near real-time reconnaissance, surveillance, identification, target acquisition (to include cueing) and intelligence gathering;

- To provide comprehensive sensor and fusion capabilities for gathering, collating, evaluating, and disseminating information;

- To provide the ability to conduct information warfare and achieve information dominance;

- To provide effective, reliable, and secure, multilingual communications across functional areas and down to the lowest level.

As the explosive growth in the scale and importance of the role played by information systems continues, today's technologies will exhibit limitations that will become increasingly intolerable. Particular attention will need to be given to means for improvement in the following fields:

- Sensor and information correlation and fusion;
- Multispectral sensing, to include passive and active, acoustic, electro-optical, radar, et cetera;
- Real-time target identification;
- Improved, and possibly automated, battle damage assessment capability;
- Physical and electronic protection of friendly C^4I systems;
- Ability to influence, disrupt, attack, deny, and destroy enemy C^4I.

3.2 Mobility

With the NATO area of operations less clearly defined, and with the expectation of fewer resources due to shrinking defence budgets, mobility will remain a critical function. NATO forces may be called upon to operate in any part of the world, possibly with little or no host-nation support. Therefore, commanders must be able to deploy and recover suitable and sufficient military capability, in a timely manner, to meet any task. Mobility will be required to conduct and support offensive and defensive missions, as well as humanitarian support and non-combatant evacuation operations. Essential to future mobility concepts will be the capability to conduct high volume operations with minimum external support, and near autonomous operations into, and out of, unprepared areas.

To meet the higher demands on mobility, particular attention should be given to means for improvement in the following areas:

- Integrated mission planning;
- Real-time situation updates, in particular threat updates, to improve transport survivability;
- Ability to operate into, and out of, low-quality airstrips, with minimal need for ground servicing, maintenance and traffic control infrastructure;
- High-precision cargo delivery by air drop.

3.3 Survivability

Survivability of NATO forces and capabilities, to enable continued and effective force application in achieving mission objectives, will remain critical to mission success. Offensive, defensive, passive, and active measures will continue to expand and increase in complexity. They will also continue to challenge the application of technology to ensure NATO force survivability. Selective enemy measures, across the spectrum, targeted at the weakest component of NATO's most crucial capabilities will correspondingly require equally selective countermeasures to neutralise these threats. In particular, the growing dependency on C^4I and computer elements make their survivability essential for the successful conduct of operations.

Survivability of capabilities essential to mission accomplishment in the aerospace environment, as well as the survivability of support areas, are expected to continue to demand the following:

- Protection of information systems, communications, air vehicles, support bases, and forces by passive measures and through active means, which will cover the entire threat spectrum;
- Combat system designs having adequate levels of redundancy and self-adaptive capability for reconfiguration in the face of physical or information damage;
- Provision of an effective extended air and space defence system against the full spectrum of threats which operate in the aerospace environment.

Particular attention should be given to means for improvement in the following areas:

- Improvements in Suppression of Enemy Air Defence;

- Self-protection, both active and passive, against the full range of threats (defence shield against attacks from all axes, by all threats);
- Mission planning improvements;
- Distributed information architectures (SATCOM), to ensure survivability through redundancy;
- Hardening and reduced vulnerability of space systems;
- Air Defence, to include theatre ballistic missile and cruise missile defence;
- Defence against directed-energy weapons;
- Defence against NBC weapons.

3.4 Mission Effectiveness

The goal of the commander is to achieve the required objectives with the most efficient use of his resources. In a battlefield context, he must optimise force structures and systems to enhance their ability to detect, identify, engage, and destroy or neutralise enemy targets. He must be able to achieve this in all environmental conditions, over long distances, with minimum friendly casualties and limited collateral effects.

Mission effectiveness takes in all elements of information, mobility, survivability, and sustainability. With the widening of the spectrum of NATO missions, effectiveness may include the ability to fight in non-traditional roles, which could include combating terrorism, drug trafficking, and smuggling. However, in any role, mission effectiveness will continue to depend on the ability to project combat power efficiently and effectively.

To achieve this, we must have these capabilities:

- To develop and employ flexible, multi-role, all-weather, 24-hour-a-day mission-capable air and space platforms;
- To develop and employ a range of weapons capable of achieving the desired effect, with adequate control of the level of casualties and collateral damage;
- To provide an optimum level of realistic preparation for NATO forces, across all levels of command and for all missions, before conducting required operations;
- To improve the capability of systems to assist the human in executing military tasks, including optimisation of human/system/equipment interfaces.

3.5 Sustainability

In an ever more diversified set of possible contingencies, sustainability will become an ever increasing challenge. Furthermore, all actions necessary to ensure that NATO can fulfil its directed missions, when and where needed and for the duration required, will have to accommodate the evolution of recruitment, mobilisation, and training throughout each member Nation, old and new. Out of area operations for the defence of NATO vital interests, as well as for peace support and other operations, will further highlight the dependency on infrastructure and support.

In a wider NATO, interoperability of main equipment, interchangeability of combat supplies, stockpiling, and localisation will all increase in complexity. More than ever, the standardisation of equipment and procedures, and a weapons development and procurement process that minimises the time and cost to design, adapt, deliver, and support mission critical systems and stocks when required, will be crucial to success. Techniques such as virtual manufacturing and on-demand production will support this goal, but it could require the redesign of existing military and industrial structures.

To cope with these challenges, specific attention should be given to the improvement potential in the following fields:

- Reduced production and life-cycle costs in spite of smaller force structures, including the use of flexible manufacturing systems, modular design, and adaptable software;
- Modelling and simulation techniques, including virtual development, test, evaluation, and production;
- Military/civil dual use;
- Independence from technical changes, adaptability to technological improvements, and expansion capability;
- Multi-mission capable systems;
- Coordinated R&D and production in NATO to ensure compatible systems and to maximise production runs.

4. INFORMATION

"Knowledge is power". The art of war pivots fundamentally on the ability to make the right decision at the right time. Increasing friendly knowledge and degrading the adversary's knowledge of the battlespace are fundamental to successful warfare.

Throughout history, technological advances have changed the way wars were fought. In past ages, we have witnessed large armies pitted against each other in wars of pure attrition. The Industrial Age spawned technology which led to greater lethality and mobility, affording smaller forces the potential to defeat larger ones. Currently, we are experiencing the impact of "Information Age" technologies on the conduct of warfare; the dimensions of the battleground are expanding temporally, geographically, and "informationally".

Some people claim that a third wave war-form, following the agrarian and industrial era, is taking shape, with a new breed of "knowledge-warriors" - intellectuals in and out of uniform - dedicated to the idea that knowledge can win or prevent wars[1].

Figure 4-1 illustrates the complexity of the situation of warfare in the "Information Age". The range of activities spans from competition in the economic and political arenas to full-scale military conflict. "Information Warfare" can take place anywhere within this spectrum, with the military operations focused at the tactical level through "Command and Control Warfare". Actions in one domain may have far-reaching and unpredictable impacts in another. This "ripple effect" may be the greatest challenge for the conduct of operations in a high-intensity information environment.

Huge amounts of information, gained through systematic scanning of all kinds of data bases and documentation and through information processing of actual sensor data, will be available in computers by 2020. This information can be used for substantiating world models (high-level dynamic knowledge bases), including models of mission task, conflict/battle environment, mission systems, human operators and commanders involved, et cetera. These knowledge bases can be

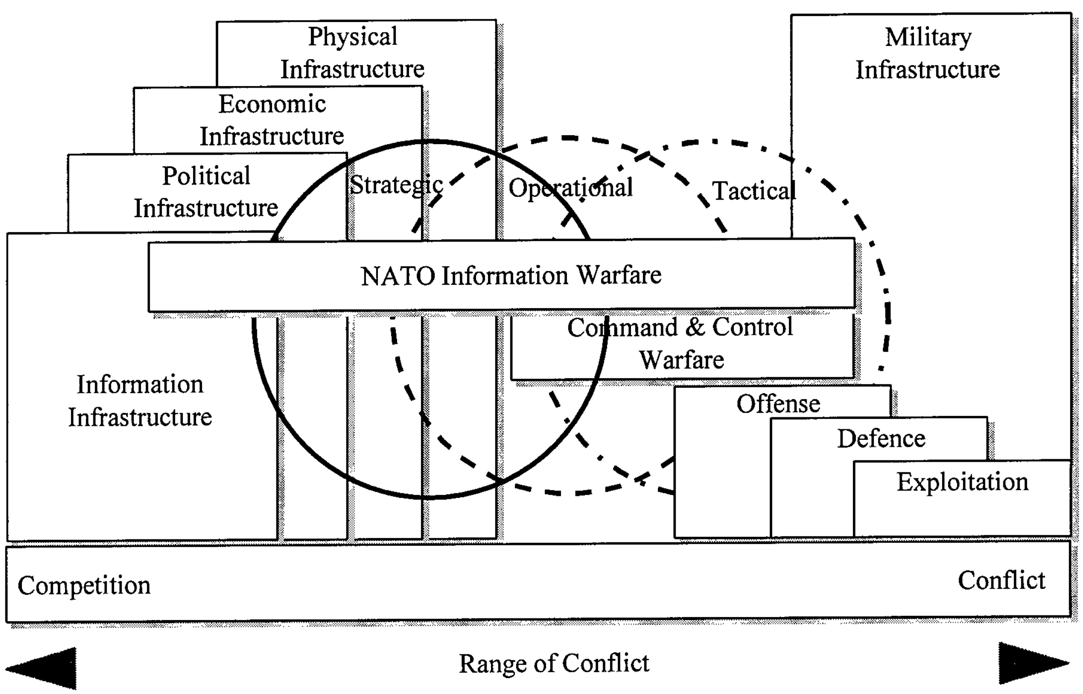

Figure 4-1: The Range of Information Conflict

[1] See, for example, Alvin Toffler's *The Third Wave*.

decisive in many ways, and they will become central resources for gaining superiority over adversaries.

Availability of comprehensive knowledge will lead toward full picture information availability, autonomous function, and highly human-operator-centred mission management functions. It will also provide the basis for knowledge-based combat identification.

The successful exploitation of these resources will require improvement in the following areas:

- Knowledge acquisition and representation,
- Knowledge maintenance and consistency,
- Accessibility of real-time knowledge from all friendly command stations,
- Hardening knowledge bases against access by adversaries.

This progress will occur, mainly, because these areas are of paramount interest in civilian life. As a result, in the 2020 scenario, a wealth of new methods and tools will be available to acquire and exploit huge amounts of data. The process will be quicker and cheaper than the time consuming processes available today, and will provide tomorrow's leaders with a high-resolution, reliably accurate, and up-to-date "picture" of the world. The overall goal is to enhance the capability to fully exploit the information available.

This goal will be achieved as a result of more effective integration of battlespace management tasks based upon interoperability in the structure of operating elements and close to real-time information, with system-wide consistency at the different management levels.

4.1 Command and Control

Command and Control systems are key resources in the fight for information dominance over any adversary. Equally, they are vital elements in the efficient execution of any NATO mission in peace or war. The force which is able to collect, analyse, and exploit data most efficiently will enjoy a considerable advantage.

The technological challenges of command and control begin with the acquisition of data and proceed through the processing of information, its movement and dissemination, and its presentation in a suitable form to the user.

Information Acquisition

To meet this challenge, situational awareness - a high resolution "picture" of objects in space, in the air, on the surface, and below the surface, be they concealed, mobile or stationary, animate or inanimate - must be provided. Within the next 25 years, real-time (i.e., with a time delay which is inconsequential for the application) dissemination of reconnaissance, surveillance, and target acquisition (RSTA) data will be possible at all desired levels of command, without system or operator overload.

It is expected that sensors will cover the electromagnetic spectrum, with a significant increase in performances such as spatial and temporal resolution, precision, and robust automatic target classification. These sensors will be hardened against countermeasures. Due to good prediction or estimation of the operational situation (propagation conditions, clutter levels, et cetera), they will achieve optimum performance within the limits set by the environment. As an example, airborne as well as spaceborne, SAR (Synthetic Aperture Radar) is widely independent from weather, has day/night capability, and has penetration capability into foliage, vegetation, and dry soil.

Improvements will be made toward the goal of precisely detecting thousands of moving, as well as stationary, targets (possibly including stealthy platforms) and to identify and characterise them, even in adverse weather conditions and terrain (using Moving-Target-Indication (MTI) and Automated Target Recognition (ATR)). These improvements will result in a high level of confidence in the knowledge of own operations, enemy operations, and third party forces. They will also allow commanders to confidently know (or predict) and understand enemy plans and intentions.

The true challenge is not only to collect information on objects with much greater fidelity than is possible today, but also to process the information orders of magnitude faster, and to disseminate the extracted information instantly in the desired format.

Information Integration and Fusion

The improvements in sensors[2] will be complemented by advances in:

- The processing of greatly increased volumes of data (many terabytes per day), using multiple types of information (including new and archived information);
- Automated screening and extraction of key information;
- Advanced, miniaturised processing hardware and software that will allow data fusion (such as fusion multiprocessing of improved resolution electro-optical and synthetic aperture data) and ATR to be accomplished at or among sensors or airborne platforms.

Individual information sources (human observation, various sensors on various platforms, ELINT, SIGINT, reference databases, et cetera) each provide data that represents a partial view of the battlespace. It is the task of the command information processing system (an individual warfighter's brain, a human-based data fusion organisation, or an automatic system) to extract from the ensemble of source data a picture that is a usable, and useful, approximation of the full picture needed by the commander.

The improvements that are taking place in the individual capabilities of the various information acquisition systems are generally accompanied by a corresponding increase in the volume of data output for any given target set. Sensors of all types will have higher geometrical resolution, will be multispectral, have multiple modes, and will proliferate on all kinds of platforms (aircraft, helicopters, UAV, spacecraft, weapons, et cetera). Intelligence gathering systems will also produce a vast amount of data.

In addition, accessible distributed knowledge bases of world knowledge should be available to represent all combat-relevant domains and objects, including static and dynamic models of the possible adversary's assets, strategies, and tactics.

This increase in data volume contributes to the higher quality of detail to be delivered in the final picture, but its growth far exceeds what is intrinsic in the recognised picture. Thus the process of data correlation and fusion serves two purposes:

- Enhancement of the information value. Correlation and fusion of several information sources are able to provide information that none of the individual sources is able to provide on its own. They are especially used to distinguish actual targets from decoys; it is very difficult to devise a decoy representative of a target in several frequency/spectral bands;
- Decrease of the data volume. Fusion of several information sources produces better and more concise information. In that sense, it plays a complementary role to data compression techniques.

Optimal combination of the outputs of several sensors by data fusion will not only increase knowledge about the characteristics of targets, but it will also enhance detection probability, reduce false alarm rates, and protect against jamming and/or spoofing.

Use of correlation and fusion techniques on a wide scale implies technical improvements in the following domains:

- Real-time processing (will require some thousands of MFlops (Millions of Floating Point Operations per Second),
- High-speed communications,
- Data fusion algorithms,
- Human-machine interface,
- Accurate time/space positioning (see insert below).

Time/Space Positioning

Future Global Positioning Systems (GPS) will be both more secure and more accurate. Security will be provided against jamming by increasing signal strength at the receiver; cryptographic security will be enabled by electronic key distribution. The USAF New World Vistas report projects accuracies in the range of 30 cm (three-dimensional positioning) and 1 ns for system time and time transfer. Such position accuracy is essential for the realisation of systems for the fusion of high-resolution information based on data from spatially separate sensors.

[2] For further discussion of future sensors, see Chapter 6.

Fusion is very dependent on the user demand, and the user's tools must meet many demands. It is a very difficult challenge to satisfy the various users with optimal exploitation of raw data. A choice must also be made: is data fusion best performed near the information sources, or near the user. Fusion early in the process will decrease the volume of data to be transmitted to the users, but it may not fulfil the user's needs as well as if the whole information were sent to each end-user, where user specific processing could be performed.

For any approach, a NATO-wide infrastructure, with many centres and sources integrated by the information highway, will be required for disseminating the processed information.

Communications - Military Information Highway

Communicating information (voice, message/data, graphics/images) is, and will remain, a most vital aspect of crisis/conflict management, peacekeeping, and warfare. Today, terrestrial/fixed communications technology is going through a revolution generated by photonic/fibre-optic and signal processing techniques.

Fixed infrastructure and related elements (headquarters, et cetera) will, in the coming years, be able to have access to essentially limitless communications capacity. The associated information systems support will grow, based on these large capacities. However, there is no technological breakthrough anticipated for provision of increased communications capacities to the mobile/tactical user; only small, incremental increases can be expected. This means that such users must use capacity much more efficiently. Any possible breakthrough in tactical bandwidth would be reliant on Line-of-Sight systems - such as spaceborne and airborne relays. Airborne relay systems would be reliant on gaining and maintaining air superiority.

Radio communication will be the essential element of all tactical operations (and other mobile operations), and a significant component of higher level command and control requirements. As more efficient communication techniques are developed, more sophisticated ECM and ECCM will also continue to be developed in parallel. Radio communications will remain vulnerable to hostile action; fixed radio communication systems will be more vulnerable than mobile systems[3].

Packet Switching

The most generic and powerful means to reduce the risk of disruption of communication systems is media diversity, or proliferation of available media through open networking. For data message systems, the use of "packet-switching," which provides routing over diverse media networks, is an additional possibility. Packet switching involves dividing a data stream into small "packets" which can then be sent individually at various speeds along any available route within the communications network. As needed, the receiver can re-establish the correct sequence for packets received in the wrong order. Such systems allow for optimal utilisation of network resources.

It will be possible to "packetize" real-time speech, as well as video and standard data, with the proliferation of "fast-packet", or ATM (Asynchronous Transmission Mode) techniques characterised by efficient multiplexing and unified switching. Since there is a burgeoning civilian market for ATM, and because there is already a high degree of standardisation, ATM offers great promise for military customers. Highly interconnected networks and associated protocols/standards, such as those used for the current Internet, combined with digital wireless systems such as GSM, will provide the basis for much of future communications; ATM will provide the technology for larger capacities.

It is expected that, in the future, moving images will be transmitted to show, on each user display, moving maps, and the faces of talking people. A set of new technologies, under the generic title of "Military Information Highway", will be necessary to support these requirements. The technical advances necessary to realise the Military Information Highway are:

- Self-organising system design,
- Highly flexible networks,
- Appropriate network protocols,
- Very high capacity, robust, and secure data links,
- Active and intelligent control of data distribution,

[3] Further discussion of the technologies of Communications Electronic Warfare/Defence may be found in Annex 1.

- Hypermedia facilities,
- Methods for system interoperability analysis and establishment of standards,
- Hardening against intrusion, eavesdropping, et cetera.

Advances in distributed high-speed processing, combined with software for knowledge-based learning by intelligent agents, and with interoperable high-capacity communications links, will support information processing and dissemination within the infrastructure and along military information highways that connect tactical units to the infrastructure.

Commercial development of fibre-optic technology will provide gigabytes per second terrestrial and undersea connectivities. Concepts such as Global/Theatre Broadcast Services (GBS/TBS), using satellite and UAV relays, provide both high-capacity multi-channel, (e.g., "100+ TV channels") and 2-way connectivity, for selective "user pull" of information, plus "smart push" by "anchor desks" within the infrastructure.

The TBS concepts are being enabled by long endurance UAVs. These concepts will provide options for improving robustness (e.g., resistance to electronic countermeasures) of connectivity, and for supporting sensing (and potentially armed reconnaissance) for forward elements.

Developments in laser links and optical switching and modulation will further enhance these capabilities.

As communication systems become increasingly networked and multifunctional, management of these systems will become complex and highly automated. The disruption of such systems by malicious software (viruses, worms, et cetera.) will become an increasingly significant electronic threat, in some cases possibly more so than classical threats posed by jamming, spoofing, et cetera.

For joint and combined operations, it is essential for all actors on the field to have identical means for information exchange - or at least means capable of interfacing with others properly and easily. Today's C^3I (Command, Control Communication, and Intelligence) systems are really systems of systems, where interoperability was not part of the original design. To meet future requirements, it will be necessary to be able to use, or to cooperate with, others' information exchange systems - without the need for too many, too complicated, or too costly conversion utilities. This will require attention to:

- Interface techniques and standards,
- Common protocols,
- Interchangeability of components,
- Common representation of semantics and pragmatics (Data and Knowledge Engineering).

To achieve interoperability, it is essential that, from the beginning of their conception, software tools and utilities use similar structures and interfaces. As a first step in the process of implementing interoperability, one has to automate exchange of information. As a second step, it will be necessary to optimise:

- <u>Cueing of tasks</u> in order to reduce the workload,
- <u>Cooperation protocols</u> in order to solve potential conflicts.

Interoperability of allied and coalition forces will also be greatly facilitated by automated machine translation of operational orders, logistics data, and oral commands. To assure rapid, unambiguous understanding amongst military forces, commercial machine translation products will be adapted for the tactical and strategic domains.

Synthetic Environments

Future developments in the technology and practices of synthetic environments (see insert on following page) will have a major impact on all levels of military command and control, particularly in the following key areas:

- Facilitating the assimilation, integration and presentation of the multiple information flows available to the commander;
- Projecting the likely consequences of alternative courses of action;
- Assessing the capabilities, plans, and intentions of an enemy, and the implications of enemy actions;
- Preparing, evaluating, and refining plans for missions to be undertaken;
- Post-operation analysis;
- All aspects of training.

Fundamentally new command capabilities will emerge. Through advanced display methods developed for synthetic environments, the portrayal of information derived from many sources (including remote sensors), will provide battlefield commanders with the geographic location of virtually all battle assets, and with the latest intelligence information on opposing forces. Robust models would then be employed to simulate possible actions and reactions in faster than real time. Synthetic environments will allow commanders to learn, in real time, the potential results of their decisions in combat situations. In addition to simulating potential mission performance, other components: life-cycle support, logistics, provisioning, et cetera, can be simulated. This will allow rapid assessment of operational campaign plans against re-supply plans, stockage objectives, and so forth. Using the system to explore a number of potential decision alternatives could result in improved performance by the unit, and improved force application decisions by the command. Multinational battle staffs could develop and test various strategies to determine most likely outcomes, and evaluate plans to ensure effective support and coordination.

The evaluation of command and control operations, and the training of command and control personnel, will also be improved by synthetic environment concepts and technologies. In this and other areas, the result will be a fundamental shift to methods that require fewer resources while producing more realistic and challenging training. Synthetic environments will allow personnel to become expert on specific equipment in an environment that is not otherwise available, due to safety restrictions or the physical limitations of the training space. Entire organisations will train as teams, using their equipment while reacting to a simulated enemy's actions, and acting with the concurrent operations of other friendly forces. Thus a number of simulations of a battle could be run credibly, with different actions and reactions taking place. They will be realistic options, but will be randomly introduced in order to make the training more varied, and to better equip the team mentally to deal with alternative situations.

<u>Synthetic Environments</u>

The technology that is driving the information revolution is leading to profound changes in how simulation is used in all aspects of operational decision making, as well as in training and in commercial development, testing, and production. These changes will cause an evolution from the most advanced systems of distribution simulation toward "synthetic environments" - integrated collections of simulations characterised by:

- Ready access to global data bases and models,
- Constant real-time update from real world sources,
- Immediate response to user inputs,
- Sophisticated presentation techniques, usually - but not exclusively - visual, to assist the user in interpreting and manipulating massive amounts of data.

If fully realised, the synthetic environment concept will make powerful, highly credible analytical capabilities accessible throughout the information networks of the future.

The variety and scale of joint task force scenarios in NATO makes it both impractical and costly to consider staging large exercises as the principal means of evaluating new systems, force structures, tactics, and doctrine. By using synthetic environments, scenarios can be created to complement such evaluations.

Figure 4-2 is an illustration of the ability to mix and match real and virtual players in a distributed simulation environment. The virtual players could either be created on-board the AWACS, or up-linked from the ground from a virtual AWACS. In a beyond-visual-range environment, virtual players can be injected seamlessly. The implementation of this concept requires the ground-based systems to be built to the same architectural standards, and to have functional compatibility with the airborne system and associated simulators.

Such simulations would also be useful for mission rehearsal. Pilots could 'fly' their mission while en route, reacting to a simulation generated within the cockpit, based on the syntheses of real-time sensor data on the threat and friendly situations with terrain models, et cetera.

An example of this type of application is the US Navy Joint Tactical Combat Training System (JTCTS) being developed to confront the cost problem of maintaining and operating large aggressor aircraft units and ground-based air defence threat for training purposes. JTCTS will provide the US Navy with an at-sea combat training capability for an expeditionary force, and

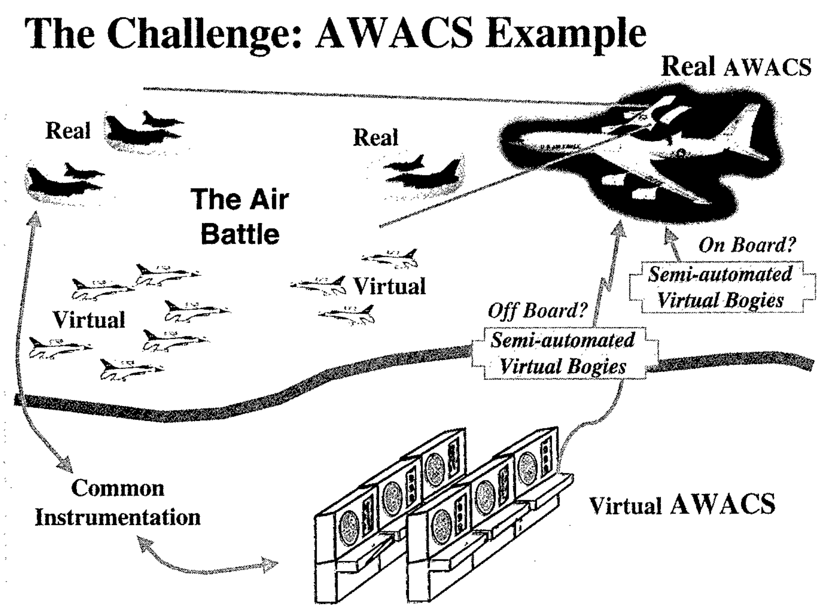

Figure 4-2: Distributed Simulation - AWACS Example

a land-based capability for aircrew training. It will include both fixed ranges and a mobile capability. One of the objectives of the JTCTS program is to provide realistic threat representation, via data links, to up-link air defence and other threat information. This will be one of the first large-scale training applications of distributed simulation technology and will include simulation of on-board platform sensors.

Architectures

Constructing an information architecture to selectively capture, process, and use information is a critical priority. The fusion of relevant data will require a major expenditure of time, money, and effort, but it is essential to deal with both the problems and the opportunities we will encounter in 2020 and beyond. One key element in achieving this goal will be foreseeable advances in technology: sensor development, increase of computation power, improvement of information processing algorithms, and miniaturisation.

Command, control, and information processing systems exist at a wide range of levels of command - from the Supreme Commander to the individual warfighter. However, at each level the basic functional control loop encompasses the same fundamental activities, aimed at the achievement of the goals set by the commander.

The basic component activities are:

- Assessment of the state of the operational environment, and of all relevant participating military elements, both hostile and friendly;
- Planning and evaluation of possible courses of action to be undertaken;
- Decision on the plan of action to be put into effect;
- Management of the execution of each chosen action;
- Re-evaluation of the situation vis-à-vis the goals to be achieved.

In a sense, the multitudinous command, control, and information processing loops at various levels are all part of a single complex loop, since the goals for all subordinate levels are contributions to higher level goals and, ultimately, to the achievement of the Supreme Commander's goals.

The existing command structures have evolved through long experience of wars and other military operations, and they tend to be strongly hierarchical. Such structures are effective - in keeping the level of detail to be handled by each commander appropriate to his or her particular

task, and robust - in that pursuit of assigned tasks can proceed even if lines of communication between levels of command are subject to interruption or are limited in capacity. The supporting systems architectures to serve these command structures have evolved in parallel. Generally linked physically and organisationally to the command structure, these systems architectures have also become strongly hierarchical.

Although well proven, these hierarchical systems architectures have some weaknesses that the advance of command, control and information processing technology will make it possible to overcome. These weaknesses may be summarised as:

- Information available at various points in the overall command structure is not brought together and made available in suitable form to each warfighter able to exploit it;
- Appreciation of the overall picture presented by the total available information may be impeded by the partitioning of the organisational and information structure;
- The physical and organisational architecture of a hierarchical command structure provides limited flexibility and speed to deal with new types of missions or radical changes in the combat situation.

The central features of the improvements offered by advancing technology, as they relate to these weaknesses, are:

- The ability to provide a very high-capacity, secure, flexible, and "self-organising" communication system (a military 'information highway');
- The ability to acquire, communicate, and effectively exploit, at all levels of command, a vastly increased quantity of battle relevant data, without overloading commanders or operators.

Such an improved communication system could rapidly and efficiently support any desired geographical, functional, or hierarchical engagement of command structures; it could make the entire information processing capacity and knowledge base possessed by friendly forces (including out-of-theatre resources) available to any commander. It would be built upon the major progress on-going in the fields of data fusion, and of machine intelligence applied to the task of command assistance. These broad improvements will provide the basis for a much closer integration of management loops that exist at various levels. They will provide much greater flexibility to restructure the overall command organisation.

Interoperability between two nested[4] mission management components with possibly overlapping environments, fundamentally requires:

- <u>Information consistency</u> for situation assessment of their respective theatre environments through netting of information sources and communication links;
- <u>Synchronisation</u> of management cycles;
- <u>Minimisation of cycle time</u>, in particular for the command and control components. It is crucial to react quickly, to keep the elapsed time extremely short between the sensing of a critical condition change in the environment and the reaction;
- <u>Improved vertical and horizontal integration</u> and support across management components (e.g., strike and defensive control and support).

Therefore, key functional elements for integrated management in a cohesive structure include:

- Netted, multiple sensors (airborne, space and surface-based) for reconnaissance, surveillance, and target acquisition;
- Remote and local infrastructure support for processing and exploitation of information;
- High-capacity connectivity through fibre-optic cables, plus 2-way and broadcast services through satellite and airborne relays;
- Networked (on-line) surface and airborne combined intelligence and battle management nodes and capabilities that

[4] Nesting refers to the tendency of management loops to be contained within larger loops. Loops also often share common links with other loops.

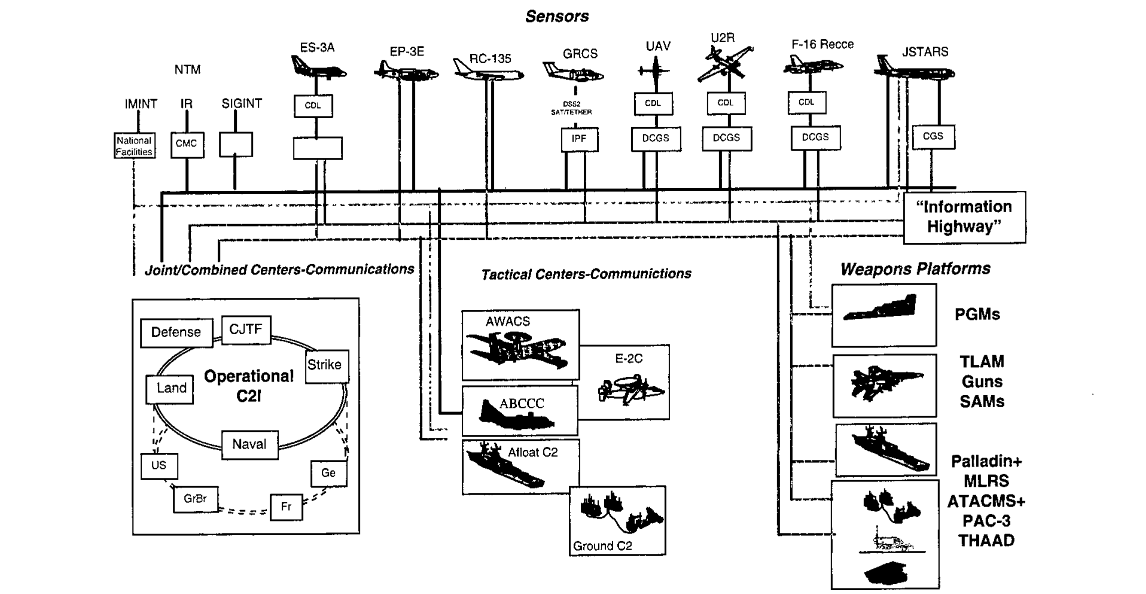

Figure 4-3: Integrated Mission Management Structure - Illustrative Example

can provide deliberate and dynamic planning and control of offensive and defensive operations, sensor tasking, information management, and force management;

- Optimised human-machine interaction between operators and commanders and their highly intelligent mission systems, machinery, and weaponry.

The challenge of realising overall campaign management as an integrated task across all operating levels already exists. The higher the management level, the more the response time increases, and the less support is available for the commanders from automated systems. Prominent complaints like that of Davis of the US DoD[5], "...despite successful space-based missile warning, navigation, and other operations in the Gulf War, these systems failed to work together ...", illustrate the current deficiencies.

Nonetheless, with the advent of new technologies in sensing systems, in particular for reconnaissance, surveillance, and target acquisition, powerful knowledge-based computation in support systems and ultra-high bandwidth of interoperable information links, dramatic changes can be envisioned.

By the year 2020, it can be expected that the process of integration of mission management across all operating levels will go much further than today. Almost all command and execution levels will be internetted more effectively - both within the NATO area and, for combined joint task forces, in out-of-area situations. Relevant information at a high degree of comprehensiveness can be made available in a timely fashion for each of the operating elements (components, nodes), across all levels, by new types of sensing systems and interoperable communication links. Thus, situation awareness will be available, to the degree required, at each component (see Figure 4-3).

The interaction of humans with highly intelligent mission systems will be improved by human-centred automation[6]. This will take advantage of increased automation; embedded processing at sensors, (potentially extending from today's remote control of sensors on UAVs to future Unmanned Tactical Aircraft), and other enhanced information capabilities; virtual environments and knowledge acquisition about behavioural strategies; production rules; and action schemata of mission management personal.

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[5] Robert V Davis, First Deputy Under-secretary of Defense for Space, IEEE Annual Aerospace Applications Conference, February 1996.

[6] See Chapter 5.

Vision

Information networks consisting of terrestrial, space, and airborne links, which connect both remote and local infrastructure centres and tactical (surface and airborne) centres, can be readily and flexibly established. Thus they will be optimal for supporting major/lesser regional conflict needs, as well as a variety of operations other than war.

Combat planning and management for airspace operations (strike and defensive, including cruise and ballistic missile defence), sensor tasking and management (e.g., UAVs), and operation of supporting assets (search and rescue, tankers, surface-to-air missiles, SAMs), will be enhanced by information network developments; and by new software for deliberate and real-time planning and monitoring of such tasks as battle damage assessment, identification of assets, et cetera. These developments will permit increasing on-line collaboration and assessment by intelligence and operations personnel. Potential enhancements, such as dynamic tridimensional display interfaces and environmental modelling for battlefield planning and prediction, will support these tasks.

Support from local infrastructure elements for mission simulation-prediction and training "from the operator's seat" is also being enabled by the developments noted above and by technologies for generating synthetic/virtual environments. Ongoing data processing developments to permit linking live and virtual environments/operations should significantly enhance the realism and utility of this support by 2020.

These expected technology advances will make it possible to operate inside the opponent's decision and action cycles by responding to, and increasing the capacity for:

- Situation monitoring (and fusion) of thousands of events in tens of minutes;
- Planning/development of integrated orders - for example, tasking orders with hundreds of targets and updates in hours, with tens of targets per minute in peak periods;
- Tasking tens of sensors and directing thousands of actions per hour in peak periods.

Support of major military operations will be greatly enhanced through the application of information technology to the logistics planning and execution monitoring process. This will be particularly valuable during large deployments, where logistics automation tools will provide cost savings through efficient allocation of material. The logistics automation tools will be integrated into the command and control structure to seamlessly integrate support tasks with a high tempo of operations.

Looking towards 2020 and beyond, a progressive evolution in command and control from the existing, rather compartmentalised, rigid, and hierarchical structures toward increasingly integrated, yet flexible and versatile, structures can be foreseen. In these structures:

- Information boundaries between the various levels of command, and between command and related specialised support functions are largely eliminated;
- The information infrastructure is flexible, allowing for rapid, yet secure, reconfiguration of command functions, regardless of geography and according to operational need;
- Sensing and intelligence systems will provide an immense amount of detailed, highly consistent, and up-to-date information on all aspects of the battlespace. It will include details of all friendly and enemy resources, selected according to each warfighter's needs;
- Each warfighting decision maker will be supported by very powerful machine assistance, to illuminate and facilitate the taking of more successful command decisions faster than any adversary;
- The waging of information warfare will be as crucial as the waging of physical warfare.

4.2 Warfare in Information Systems

Information warfare, in a general sense, is as old as warfare itself. Attempts to confuse an enemy as to one's intended actions, to discover more of an enemy's intentions than their commanders intend should be known, to corrupt or destroy enemy information about all aspects of the battlespace,

and to undermine an enemy's will to fight are classical military activities. In their basics, these activities will continue. There will, however, be some shift in the balance of constituent activities, reflecting a number of changing realities, notably:

- The changing character of the military tasks which may confront the forces of the Alliance in the decades to come (as discussed in Chapter 2);
- The explosive growth in the use of digital communications and information processing systems to reinforce the warfighter's capabilities;
- The related growth in the opportunities and benefits for an enemy to attack such systems, using the same methods and technologies as those of the victim systems;
- The growing exposure of all types of military activity to media coverage - the degree to which information (which may be true or false) may pass to enemies and to the general public through media channels - in many cases, these channels may significantly distort the initial information content;
- An increasing dependence of military information systems upon components contributed by the commercial world.

The Information Society

In the rapidly growing civil "Information Society," we are witnessing an ever-widening and deepening use of information as a commodity, a tool for the more efficient transaction of business, and an ingredient of recreational activity. Increasingly, the use of information for these purposes takes place in near real time. The power and extent of the communications infrastructure supporting the exchange of data are growing with extraordinary speed, as is spectacularly evidenced by the Internet. This accelerating progress is creating a demand for diverse information, associated tools, and more importantly, a wish for instant access by the end-user. The first effect of this demand will be the increasing availability of information, both in type and volume. The amount of information potentially available to an end-user will increase almost exponentially with time; hence, the probability that any required data is available somewhere will increase, although probably not as rapidly as the size of the accessible data set.

In parallel with this growth in information provision, there will be an unceasing demand for increased processing power to exploit this data-rich environment. The development of tools ("intelligent agents", data mining toolsets, natural language querying, fuzzy searching, et cetera) will become the driving force that will be harnessed to deliver "added value" information provision. This will be accompanied by development of improved data fusion capabilities to enhance the available knowledge and, in tandem, deliver increased certainty related to such knowledge.

Within the Information Society, the increased volume of information and its associated "value-added" services will foster the recognition of information as a commodity that will be exchanged and traded in the same way as other goods. The globalisation of communications will stimulate this type of trade, so that new products and services will evolve to guard/protect information in a similar way to current financial market transactions. "Free" information/services will earn revenue through advertising or increased market share for follow-on products. Hence, within 10 - 15 years, a new set of information markets will develop and grow, fuelling advances in both hardware and software to meet customer demands. In parallel with this market growth, there will be a consequent need for increased communications bandwidth coupled to "point of entry" flexibility, i.e., mobile users, dynamic allocation of bandwidth, et cetera.

One significant consequence of the explosive growth in communication and information management is the increasingly pervasive role of the mass media in bringing news of events, world-wide, to the homes of the general public - with very short time delay and in graphic detail. Such news coverage exerts a very powerful influence upon public opinion and, consequently, upon the decisions and actions of governments and other bodies answerable to the public. Moreover, since the information that is published is only a tiny fraction of the information gathered, the news provider can have an immense effect upon the public perception of events through the exercise of editorial selectivity.

With this ever-growing quantity and variety of information being accessible, and an increasing

expectation that decision making will be based upon the availability of such information from networks of distributed sources, it will become increasingly important to have the capability to exercise "value judgement, data validity criteria" tools as part of the overall assessment process. There will be an increased reliance on database quality verification tools that can check source material labelling. In the future, it is likely that the use of "mirrored sites" will increase as a result of Internet-type data expansion. New tools for verification will become important as part of an overall assurance architecture for interested parties, as a means of checking the integrity of the data being retrieved. This will be particularly important if information is presented as part of a multimedia document or presentation using sophisticated data fusion engines, where the possibilities of events being misinterpreted or misrepresented will quickly multiply.

Vulnerabilities

Against this background, information warfare is expected to assume increased importance over the decades to come.

This increased importance is illustrated in Figure 4-4, which is a diagram of the US Defense Information Infrastructure (taken from the US Defense Science Board Summer Study, 1995).

The figure shows overlapping and interconnected sets of information infrastructures: fundamentally a set of concentric spheres that are central to achieving global access. The DoD (Department of Defense) Core, shown in the graphic, includes the very sensitive, very secure, National Command Authority communications.

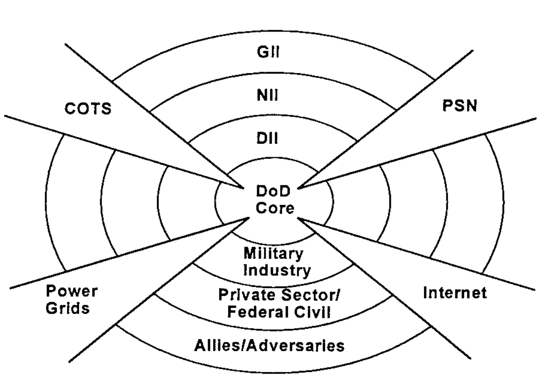

Figure 4-4: US Defense Information Infrastructure

The Defence Information Infrastructure (DII) that surrounds and includes the DoD Core is also made up of communications, computers, and data bases, some more sensitive, and hence better protected, than others. The DII ranges from systems that are tactically significant to the field commanders, to systems such as the pay and disbursement systems that are important to individual service members. The DII includes other critical components, such as the Global Transportation Network (GTN), which supports "just in time" logistics, and the INTELINK, which provides the field with direct access to intelligence information.

Enveloping the DII is the National Information Infrastructure (NII). The NII contains the many local- and wide-area networks that make it possible for commercial industry to share resources and to communicate in real time, not only within their corporate headquarters, but out to their smallest subsidiaries and field offices. The NII includes technologies and components such as Very Small Aperture Terminals (VSAT) for direct satellite voice and data access, and wireless networks that provide connectivity while affording complete global mobility. Personal Communications Systems using GSM technology provide the multi-service functionality of the cellular phones, pagers, voice-mail, et cetera, integrated into a single, hand-held device.

In a similar fashion, the Global Information Infrastructure (GII) envelopes the NII. The GII provides the cross-connects and switches that enable the United States NII to connect to, and be fully interoperable with, virtually any other nation's equivalent to the NII.

The connectivity shown by the cross-cuts of the Internet, the power grid, and COTS (Commercial-Off-the-Shelf) results in vulnerability for the entire system. Yet newer, faster, more efficient means of communication and data exchange are entering the market every month. While organisations need to be part of this revolution, they cannot afford to build and field militarised versions of these capabilities at the commercially generated pace - especially in the face of declining budgets. This leaves little option, except using the same technologies and the same systems as their commercial counterparts and accepting the risks.

Use of COTS products, rather than tailored software for military applications, has a number

of consequences, not the least of which being the unknown status of bugs, software patches, glitches, and so forth, existing within the code. Additionally, there will be problems in testing. It will be very difficult to simulate all of the potential problems that might arise when using such products in combat. This increases the likelihood of these products failing in a highly stressed environment.

The COTS path will lead to a potentially robust connectivity environment, but with the added complication of emphasising standards, open architectures, et cetera. The wide availability of COTS products will provide opportunities for potential adversaries to explore and exploit their weaknesses, and to prepare to use their deficiencies as part of their own IW strategies. This will expose a variety of media and paths for exploitation, and provide a fertile area for viruses, logic bombs, and the development of covert software trapdoors.

Information Warfare Measures

The development of Information Warfare involves two related, but distinct, aspects: measures related to digital attack upon computer information systems and techniques for resisting such attacks; and measures and issues related to the integrity of data supplied on information networks. In the former context, there are a number of offensive and defensive measures which have been identified, including:

- Malicious software code,
- Deliberately engineered chip hardware vulnerabilities,
- Software vulnerability exploitation;
- Non-nuclear EMP weapons,
- Silicon-eating biological weapons,
- Cryptography/cryptanalysis,
- Deception/authentication,
- Video techniques,
- Psychological operations,
- Attacks on financial systems / trading floors, banks, telecommunications networks, computer networks of electrical distribution services et cetera,
- Disruption of air-traffic control services,
- Denial of services (flooding network/service provider with "bogus" demands/requests).

The possibility of electronic attack is, clearly, more than hypothetical. In the United States, the Defense Information Systems Agency estimates that some 250,000 attacks were made upon DoD systems in 1995, while the General Accounting Office estimates that more than 150,000 successful attacks were made upon DoD computer systems in that year. Other studies suggest that at least 20% of such attacks are made by agents outside the victim organisation. In the Internet domain, the placement of "Sniffer" programs (to identify passwords, et cetera) in Internet hosts has been observed. One estimate has placed the number of such emplacements in excess of half a million.

Defence

To respond to the threat of attack upon information systems, it will be necessary to develop appropriate security architectures. These architectures will provide essential security attributes, such as:

- Authentication to provide assurance of the identity of a person, or computer system or a process on a system;
- Access control to protect against unauthorised use or manipulation of computer or network resources;
- Confidentiality to protect against information being revealed or disclosed to unauthorised persons or systems;
- Data integrity to protect against information being changed or deleted without detection or authorisation;
- Non-Repudiation to protect against one party to a communication transaction later falsely denying that the communication took place.

Such security architectures should provide technical protection, with the limitation that they cannot protect against problems arising from captured equipment or unfaithful personnel.

To protect the integrity of information and to counter the potential for control and abuse of disseminated information, some form of quality/guardian approach will be required. Such an approach should assure users that the information provided has not been tampered with. It is likely that Internet-like services will proliferate, offering a resilient service designed to degrade gracefully. The major driver for provision of this type of service will be associated with

financial transactions, where the need for security and fidelity will be paramount. Recent examples of dedicated developments include:

- Trusted distribution of software,
- Trusted web server technology,
- Multilevel security (MLS) tools and environments (including data bases, protocols, passwords, et cetera).

It is likely that such services will realise a high degree of protection by taking advantage of new developments in algorithms for checksums, symmetric encryption, and public/private key encryption. However, these developments will probably not completely satisfy the more stringent needs for military information protection.

In parallel with efforts to comprehend and optimise the management of information, there will be important advances in the understanding and mechanisation of means for launching, and for countering, digital attacks upon defence (and commercial) information systems. The following capabilities will be required:

- Integrity and availability assurance tools,
- Risk analysis and management methodologies,
- Tools for achieving recovery after attack,
- Systems for detecting and alarming upon system intrusion,
- Tools for combating the actions of a hostile intruder in an information system.

In addition, there is a need for increased awareness, for improving anti-intrusion technology, for training in an hostile information warfare environment, and, possibly, for deception plans to protect information assets.

The ability to make value judgements based upon open source information is predicated upon an understanding of the source, which, in Information Warfare terms, is under the control of the supplier. An intelligent customer must be able to discern and measure the truth/facts embedded within presented information. The military customer risks becoming desensitised to these fundamental parameters when confronted with the "fact" that, because this information is so widely available, it must be true. The underlying threat is the growth of a belief that all of this information, made available at the "click of a mouse," will inexorably lead to the ability to make an "informed decision". The real trick will be to make sure that it is not a misinformed decision.

4.3 Summary

The future operations of NATO forces, in both combat and peace serving missions, will be transformed by the information revolution that is already under way, and whose pace may be expected to further accelerate, due, largely, to the stimulus of civil developments. This transformation will impact:

- The organisations, structures, and tools for the exercise of military command and control;

- The acquisition and handling of information;

- The means of communication that tie together the various warfighting formations;

- The need for, and means for, attacking and defending information systems.

Many of the key tools and techniques for achieving these transformations are freely available on world markets. It must be supposed that many of their advantages will also be secured by opponents of NATO. The following characteristics of information conflict merit careful appraisal:

- <u>Low Entry Cost</u>: The only major prerequisites are information systems expertise and access to important computer networks;

- <u>Potential lack of a Distinct "Enemy" Force</u>: The spectrum of potential adversaries runs from private individuals, to organised crime, to terrorism, to adversarial states;

- <u>Perception Management</u>: New multi-media techniques may provide substantially increased opportunities for deception and image manipulation activities;

- <u>Undefined Vulnerabilities and Target Sets</u>: Not knowing what needs defending radically degrades the effectiveness of classical intelligence techniques and methods;

- Undefined Response Systems: There are no developed criteria to differentiate between accidents, espionage, organised crime, and concerted IW attacks.

Information dominance will become a primary goal in warfare. The role of information in warfare will expand throughout the spectrum of conflict. The next 25 years will witness two major effects of this expansion. First, command and control processes will be based on machine-managed acquisition, processing, assessment, and distribution of a common, high fidelity, near real-time battlespace representation. Second, information warfare will increasingly focus on attacks directed against the infrastructures of an enemy's society.

Faced with these rapidly evolving new capabilities and threats, the Alliance must be resolved to act energetically to ensure that it achieves and maintains information dominance over any potential opponents.

5. HUMAN-MACHINE PARTNERSHIP

Meeting the challenge of military action has always demanded the utmost use of both intellectual and physical forces - whether in confronting an enemy in war or in keeping the peace. Just as advancing science and technology deliver ever more powerful and complex machines and systems (weapons, air vehicles, computers, manufacturing systems, et cetera) to assist the warfighter; the scale and complexity of the interactions between machines and the human, individually or in a cooperative formation, grow with equal speed. This growth, allied with the military imperative to achieve superiority in speed, duration, and intensity of operations, makes managing and optimising human-machine interactions a crucial challenge.

5.1 Human-Machine Interaction

The role of the human being will remain paramount in any military operation. However, technological advances are placing at the human's disposal increasingly sophisticated tools for executing the mission, and an exponentially growing volume of mission-related information. This presents a challenge: to create an environment for humans which will adequately deploy their unique qualities, while harnessing the full power of the technical resources available to support the mission. This challenge will be met by foreseeable progress in technology and in the field of Human Factors. For example, it will be possible to create a human-machine interface for the pilot/operator of even remotely controlled, highly capable, unmanned tactical aircraft[1], providing the situation awareness and control capability essential for successful mission accomplishment. Advances in information assessment, artificial intelligence, psychophysiological processing, and human-machine interface technology will make possible a more intimate and efficient sharing of human and machine functions.

This human-machine partnership will relieve human operators of the burden of performing tasks that do not require uniquely human contributions, while allowing them to remain fully conscious of the overall environment in which the mission is situated.

Human Models

Modelling human function (structure, motion, and performance) is essential for integrating the human into the design of new military systems. Additional knowledge about the physiological and mental functions of human operators will make it possible to develop models of performance and behaviour that can adequately represent human beings in models of system performance, training, and simulations.

In order to fully assess the human element within the system, synthetic environments need to replicate applicable environmental stressors (such as motion, high G, noise and vibration, temperature and humidity) that affect human performance. Synthetic environments also need to provide adequate sensory feedback for visual, tactile, and cognitive modalities. These advanced capabilities are just now beginning to be introduced into simulations.

Human performance models will be developed, validated, and integrated with real-time assessments to provide essential tools with which future interface designers can compare and contrast interface designs early in the design process. Physiological and performance-based assessment techniques, coupled with human performance models, will produce the essential intent inferencing information for intelligent automation and aiding. This expertise, combined with new research, will provide revolutionary tools for the crew-station design process and intelligent automated aids for operators. The first step is a validated modelling approach for predicting the impact of a given interface design for performing a specified mission.

Although there have been numerous attempts to produce predictive mental workload models in the past, it has been difficult to validate the models' predictions.

Planners and users, as well as system designers, will be given access to the "human system" as an integral part of the computer-aided design (CAD) environment through artificial intelligence, rule-based, and case-based performance models. These

[1] See Chapter 8

models and products will be available to training and distributed interactive simulation activities. Detailed, dynamic, 3-D human physical and perceptual models and simulations will be integrated as stand-alone modules into CAD systems. They will enable crew-systems designers to simulate, analyse, and test human operator performance in candidate weapon systems which exist only in the form of computer designs.

High-fidelity CAD human operator models that integrate cognitive, perceptual, and physical performance are integrated into 3-D CAD crew-system models. These synthetic human operators can perceive inputs from the CAD crew-station, process them as situation-relevant information, and determine appropriate courses of actions.

Using these synthetic human models, designers can see exactly how operators will fit into the system, what they can reach, what they will see, what they will hear and understand, what they will think, and what they will be able to accomplish; even early in the design. The models will incorporate cognition, sensory models, language processing, et cetera, and in the longer term, the cognitive engineering will be extended to deal with cooperative systems that rely upon distributed cognition. As the system design process unfolds, the impact on human operability can be readily determined, thereby reducing the risk, uncertainty, and cost. The result will be a working environment far different than today's.

Psychophysiologically Augmented Cockpits

In aircraft available in 2020, the pilot's psychophysiological state will become an integral part of the total aircraft system - it will be monitored, used to determine some aspects of cockpit configuration, and will be the basis for establishing the relative responsibilities of the system and the pilot. For example, information about G-induced loss of consciousness, excessive cognitive workload, thermal load, and fatigue will be included in equations that dynamically modify cockpit configuration, information flow, and the functions assigned to man and machine.

The merging of physiological and performance predictions will permit future systems to make much better use of the pilot resource; on-board computers will predict pilot performance in any given situation and, thus, determine pilots' needs.

The total system will be much more efficient, since it will be dynamically configured to accommodate the human operator's instantaneous state, information requirements, and capabilities, based upon predictions about their current physical and mental capabilities and detected lapses in vigilance and attention, or fatigue.

Alternative Controls

Alternative controls can reduce workload and improve efficiency within the cockpit, directly supporting the warfighter. Careful design and integration can result in human-machine interfaces which are natural, easy to learn and use, and less prone to error.

As computer systems become more intelligent, the focus will be on communication rather than control. For example, there are a variety of control technologies that might make more effective use, compared to traditional input devices, of the innate potential of human sensory and motor systems, particularly when matched appropriately with critical mission tasks. Humans might communicate with computers and other devices by deliberate vocal commands or gestures, or more subtle movements of muscles. Judicious application of alternative control technologies has the potential to increase the range of operator-system interactions, thereby improving the effectiveness of military systems and realising cost savings.

By 2020, our understanding of the relationships between electrical brain activity and the performance of cognitive and motor tasks will enable psychophysiologically based system control. For example, certain biological parameters, in conjunction with signals from the brain measured by improved EEG, might provide the foundation for developing a true state/intent-based interface for advanced aircraft. Such measures could provide a detailed picture of the pilot's state. Based on this information, on-board systems will modify the rate or format of information presented by visual or auditory displays, adapting the cockpit environment to allow a pilot to operate with maximum effectiveness.

Technology which enables pilots to operate at optimal levels at all times will give them and their aircraft an edge in military combat. It is particularly appropriate for situations in which performance decrements associated with fatigue or task overload might create a life-threatening situation.

Enabling technologies include electrodes that provide stable recordings and a method for identifying operator state from psychophysiological responses. Electrodes have already been developed for recording slow potential shifts in the electrical activity of the brain during changes in mental workload. Such measures can identify not only an increase in workload, but also the sensory area associated with the brain function that is being loaded. Thus, if visual function showed signs of becoming loaded, the feedback-control mechanism described above could switch information presentation to a less-loaded sensory channel, so that the pilot could continue to work optimally.

Other approaches under investigation include telemetry and the use of decision-making algorithms to aid in identifying operator state.

Performance Monitoring

Until recently, a master/servant relationship has characterised the roles of operators and systems. In military aircraft, information is presented to pilots via displays, and their wishes are executed in response to control inputs. The pilot has been the only cognitively active member of the team; the aircraft systems were cognitively passive. In recent years, attempts have been made to use computerised inferencing to identify pilots' needs and aid them where necessary. However, results have been uninspiring, reflecting, perhaps, the relative paucity of data available to such inferencing systems. For example, contextual data might be inadequate to identify a pilot's current cognitive state and requirements, and thus anticipate his/her future needs.

Two primary dimensions of cognitive state are mental workload (saturation degree of mental capacity) and situation awareness (how well they understand the spatial and temporal opportunities and threats present in the environment). Mental workload and situation awareness assessment are mainstays of system test and evaluation, but they are rarely assessed in real time. To be useful in the adaptive workplace, mental workload and situation awareness must be measured and analysed in real time.

Although this has been beyond our technological grasp, several emerging technologies are expanding our reach. Computerised flight controls and miniaturised physiological recording devices will provide a wealth of information about pilots' instantaneous cognitive states, which will be analysed and combined in real time by parallel neural networks that mimic human pattern recognition capabilities. Combined with information available from other systems, the essential data will exist to guide the system's interaction with the human operator. By following the ebb and flow of an operator's cognitive state, the adaptive cockpit will become a partner, rather than just a tool.

Loss of vigilance, at any level of command, can have tragic consequences. Vigilance monitoring techniques may provide a means to unobtrusively test the level of alertness of the operator and provide warning, offering the promise of vastly improving operator safety. Substantial, but not unattainable, development of these techniques will be required for military use. Vigilance monitoring may be approached along two complementary routes - direct monitoring of the warfighter's condition, and by measurement of task performance.

Direct monitoring of the warfighter's condition is based upon electrophysiological measurement. The electroencephalogram (EEG) offers considerable promise as a means to monitor human vigilance. Brain electrical patterns have been associated with sleepiness and workload. The low amplitude signals, electrode application, and correct pattern recognition form the main challenges to EEG assessment.

Electrophysiological techniques to monitor eye and eyelid movement have also been shown to be sensitive to fatigue. These are simple, larger amplitude signals than EEG, but face the same challenges of integration. These difficulties are likely to be overcome as computer interpretation of electrophysiological signals becomes simpler.

A combination of brain and eye electrical signals may provide an optimal means to monitor vigilance. More basic research needs to be conducted to resolve operational application problems. Telemetry techniques may have an advantage over cables for on-line processing. Video imaging of eye movements may help to circumvent some of the processing difficulties. These techniques require considerable, but not overwhelming, engineering developments before routine use is available.

Vigilance monitoring techniques can also be based upon the operator's performance of specific tasks, presented in conjunction with normal tasks,

or as a stand-alone performance metric. Among the approaches available:

- Embedded tasks to be performed at a required rate during the operation of the primary task. The frequency of such tasks could be increased or decreased as the need arises (e.g., during critical times of the circadian cycle). Failure to perform the task would suggest a loss of vigilance or excessive workload, which would initiate alarms or other remedial steps;
- Other performance tests are given prior to, or during, the execution of the operator's task. These tests are sometimes called "readiness to perform" or "fitness for duty" tests, and the early data are appealing. They are quick, requiring only a few seconds, and appear to be quite sensitive to fatigue and drug impairment. The optimal test would include a broad spectrum of measures including psychomotor and neurophysiological components.

When performance monitoring indicates a deviation from the intended mission profile, electronic assistance will be available to alert and assist the operator.

Electronic Assistance

The profound change which can be expected in human-machine interaction aids for commanders and weapon operators can be illustrated by the example of a cockpit crewstation.

In this environment, abstract human-like knowledge and reasoning will allow an intelligent machine to serve as a flight crew assistant to:

- Understand the abstract goals and sub-goals of a flight mission;
- Assess needed information about mission, aircraft environment, and aircraft systems;
- Interpret the flight situation in the light of the goals of the flight mission;
- Detect pilot's intent and possible errors;
- Support necessary re-planning and decision making;
- Know which information the crew needs, and how to present it to the crew in an effective way.

By this means, it will be possible to meet the essential requirements for human-centred automation in combat aircraft cockpits, complying with the following basic requirements:

- Avoid overtaxing the crew in situation assessment (i.e., to ensure that the attention of the cockpit crew is guided towards the most urgent task or sub-task of that situation);
- Avoid overtaxing the crew in planning, decision making, and plan execution; subject to satisfaction of the preceding requirement (i.e., to transform an overload situation into a situation which can be handled by the crew in a normal manner).

Recent research has also shown that monitoring brain activity during the early stages of learning a new skill may help to identify those who will have a particular aptitude for the skill, or who will learn it quickly.

Due to the lack of human-like knowledge-based machine capabilities, these important requirements for effective human-machine interaction have never been fully met. They can be met within the next two decades.

5.2 Sustained Operations

Modern warfare is conducted 24 hours a day. The accelerated pace and intensity of modern combat operations, as well as the increased emphasis on night activity, make operator fatigue an increasingly significant military challenge. On one hand, the complexity of electronic weapon systems can rapidly deliver an overwhelming workload demand to the operator. On the other hand, sophisticated equipment can increase monotony and fatigue by reducing operator input to minimum.

The principal operational human-related problem for 24-hour operations is the cognitive and physical degradation induced by fatigue, whether from sleep deprivation or from activity during the circadian performance nadir. Should a conflict continue beyond a few days, fatigue can become a steadily increasing threat to maintaining 24-hour operations.

Little is known about the long-term operational effects of fatigue and chronic fatigue. Cumulative

fatigue can occur during any sustained operation in which sleep is not permitted during an extended duty day (generally over 12 hours); and in continuous operations, in which short sleep cycles are available over several extended duty days. Unusual hours for sleep or fragmented sleep over several days can produce profound negative effects on performance. Fatigue may also be used as a weapon, wearing the enemy down by denying them sleep, or by randomly attacking during their circadian performance nadir.

Fatigue Management

Emerging technologies that enhance vigilance while awake and improve sleep during crew rest can reduce the effects of mission-induced fatigue. Fatigue can dramatically degrade the normal human response time and accuracy rate, with the potential for catastrophic consequences. Mission threatening effects can be reduced by vigilance monitoring technologies, as described above. Performance loss can also be reduced with better fatigue intervention strategies. These strategies include both non-pharmaceutical and pharmaceutical techniques that can extend the duration and quality of operator responsiveness.

Non-pharmaceutical Techniques

Non-pharmaceutical intervention techniques have progressed to a point where limited, but effective, fatigue management is possible with careful adherence to guidelines. With further work, these existing techniques will be developed to the stage of operational use. In that operational use, we may expect to see fatigue management guidelines, tailored to be effective for all levels of personnel (from senior commanders to individual warfighters) and integrated with tactical and logistics doctrines, being routinely promulgated. These guidelines will need to be frequently updated as new techniques and information become available. For example:

- The impact of environmental stressors (noise, dehydration, heat, vibration, all-weather operations, et cetera - alone and in combination, as so often occurs in operational environments) on inducing fatigue will, progressively, be better understood;
- The fatigue reducing properties of nutrition and exercise are becoming better understood, and recognised as important; suitable regimes will be built upon that knowledge;
- Successful coping strategies for 24-hour operations will become a normal part of operator training.

Sleep training may offer an effective means to promote sleep by rapidly relaxing large muscle groups while reducing stress. Proper sleep hygiene techniques need to become part of routine mission exercises. Sleep research will yield understanding of the most efficient timing of nap and sleep schedules for maximum alert performance, and careful attention to the sleep/nap environment and duration may provide hours of vigilance for a few minutes of sleep. Sleep latency is reduced at different times of the day. Taking advantage of this information will allow sleep schedules to be designed that maximise crew rest periods, minimise recovery time, and allow safer extended duty cycles.

Physiological markers may be recognisable that identify populations less debilitated by fatigue. These markers need to be exploited in selection, and may serve as a metric in training. Selection and/or training of shift tolerant individuals may fortify NATO forces' ability to sustain continuous operations.

Environmental light improves performance otherwise degraded by nocturnal circadian effects. The use of bright illumination is possible with existing lighting facilities in most planning, control, and communication environments. Bright light may also be useful in rapidly pre-adjusting circadian phase to night operations. More information regarding intensity and frequency of light needs to be developed to optimise these recent findings.

Pharmaceutical Techniques

Pharmaceutical techniques have always been effective means to promote vigilance or induce sleep, and new compounds are available that are safer (better tolerated) and more efficacious. Research into the operational use of novel and established compounds needs to be initiated to exploit their military application. The chronopharmacological and interaction effects with other militarily relevant compounds are important considerations in this effort. Improvements in existing technologies with pharmaceutical intervention need to be explored,

as in the use of pupillary dilation to enhance night vision.

Stimulants ranging from caffeine to amphetamines can provide relief from fatigue. Unlike hypnotic compounds, there are no clear guidelines with regards to substance, dosage, or timing for stimulants.

New agents (ergogenic and eugregaric compounds), like modafinil, may be better tolerated than familiar stimulants, and procedures to use them should be made available. Past experience has shown that carefully regulated stimulant administration can be very successful at maintaining vigilance during prolonged operations. The most efficient means to do so, with the appropriate situation specific controls and safety regulations, needs to be pro-actively developed.

Important new developments in sedatives treatments should be tested for field use. The benzodiazepines are well-tolerated, with much experience to support their use.

Safer, yet more potent, hypnotic compounds should be incorporated into the military formulary, like the novel, short acting compound zolpidem. The unique properties of the pineal hormone melatonin make it an appealing means to promote sleep and, perhaps, to rapidly shift biological rhythms. Combinations of melatonin and bright light schedules may provide the most potent means yet to pre-shift the circadian timing system, and to quickly prepare crews to function at peak in a new temporal environment.

Guidelines need to be developed that would permit safe use of both stimulants and sedatives. Routes of administration may be a means to automatically deliver proper maintenance doses of stimulants or sedatives. Currently, a single oral bolus of compound forms the usual dose and route. Microchip-controlled, electrophoretically administered compounds, perhaps on a wrist dosimeter, can be better timed and more accurately regulated than bolus dosing. Slow-release capsules for caffeine or other compounds have been developed, and need to be incorporated into operational use.

Fatigue awareness training may provide useful guidance for operator vigilance. Crews are not typically trained to be sensitive to their own fatigue levels, instead they are expected to overcome it. Being more alert to the fatigue experience in themselves and in others may enable crews to better gauge and respond to fatigue-related problems.

In addition to the laboratory assessment of both pharmaceutical and non-pharmaceutical techniques, campaign-level network-simulated engagements and field trials would provide essential application information for these strategies.

5.3 System Design

In the face of increasing automation and rapid changes in technology, a human-centred approach to systems design will ensure that humans maintain authority over systems functioning, and achieve flexible and adaptive systems performance. Inadequate identification of a user's requirements by such a system will lead to incompatibility between human and electronic partners, reduced situation awareness, and associated system failure. Such concerns must be addressed in designing computer-based technologies that rely on effective human-machine teamwork.

Information about effective teamwork among humans will provide the basis for deriving the cognitive requirements for a human-machine system. Systematic analyses will identify the requirements for, and correct allocation of, cognitive functions (e.g., situation assessment, inferencing and adaptation of goals, planning, decision making, and control) between human and machine. Information about procedural and perceptual knowledge specific to a particular job, vehicle, or environment, as well as emotional and motivational factors, must be captured and incorporated systematically into the design process.

The effectiveness of this partnership may be quantified in terms of increased system usability and reduced training needs, identifying those who benefit from skill-learning techniques, such as visual imagery, thus optimising training time by tailoring training methods to individual learning styles.

Mission Integration

Military missions are becoming increasingly contingent upon the "emergent qualities" of distributed cognition. That is, cognition is shared

across people, places, and environments. To be successful, warfighters must quickly and flexibly perform actions tailored to the immediate situation, while maintaining mobile, intelligent support systems. Crew members will be forced to cope with real-world constraints, information warfare, battlefield management issues, and sharing situation awareness with a group. This creates an information surround which is evolutionary, chaotic, and potentially ill-defined. Rapidly changing problems proliferate across traditional geopolitical boundaries under highly stressed conditions.

Computational neuroscience and ubiquitous computing technologies may have much to offer in addressing these concerns. Ubiquitous computing (UBICOMP) may be defined as those computing elements which are distributed as everyday objects in a warfighter's work environment (e.g., surfaces, chairs, pads, desktops, et cetera), rather than integrated into a single workstation, presenting a seamless interface between users, information, and objects. In many cases, UBICOMP concepts invisibly blend into the background.

UBICOMP may consist of many task-specific microprocessors that are coupled by wireless communications to form a shared, mobile information space. When complemented with evolutionary computing technology, the computer structures are designed to 'genetically evolve' in response to environmental, technological, and multi-operator demands in ways that are analogous to neurological functions, changing according to natural selection. The cumulative experiences that occur when adapting to complexity and change are represented in the steady state of the system, yet remain active for continuing the process of becoming more responsive to new sources of change. In this sense, computational neuroscience is indicative of a non-linear dynamic system.

Protection[2]

In manned aircraft, protection of the aircrew will remain a critical problem. One of the most rapidly developing threats is the threat to vision represented by directed-energy weapons. Three possible candidate laser-protective cockpit approaches use similar technologies, but to varying degrees. Each approach requires advanced helmet systems, large flat-panel displays, high-resolution high through-put graphics processors, decision aids, MSI (Multi-Sensor Integration), and expert systems. The present trend of technology portends that the necessary technologies will be available in the 2025 timeframe.

If the "piloted aircraft" is to be viable in an advanced laser weapon environment, there are three general solution candidates. They are:

- An opaque helmet visor,
- An opaque canopy,
- A no-canopy, or "windowless," cockpit design as shown in Figure 5-1 (on the following page).

Current helmet visors provide laser protection by including band-blocking filters, or PZLT (Lead Lanthanum Zirconium Titanate) techniques, for turning the visor opaque when struck by a nuclear flash. The problem with this approach is that a "frequency-agile" laser can "shoot" a number of frequencies, including non-visual wavelengths; therefore, the use of static, or even dynamic, filters that cover the laser wavelength spectrum quickly leads to a totally opaque "no-see-through" visor. This is the cheapest solution, but it leaves the pilot with only the information that can be provided by an HMD (Helmet-Mounted Display) projected on the opaque visor. No panel displays will be available to the pilot. Enormous improvements in display and optics technology would be required to replicate the "world" as the pilot wants to see it. This "virtual" world would have to include navigation systems and sensor data, HUD and/or Helmet Displays, and some form of outside world references.

The opaque canopy approach, using either paint, fixed, or removable structure; or an electrically-actuated canopy and windshields coating that can be manually selected by the pilot before entering the combat zone, would protect the pilot from all but the most powerful lasers. The pilot would then be flying in an environment similar to any of today's modern, all-weather fighters during an in-weather (IMC - Instrument Meteorological Conditions) attack, where there are no outside "visual" references. Improved sensors, displays, data bases, and helmet technology would, in fact, give the pilot many advantages over today's

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[2] This material and Figure 5-1 are extracted from Chapter 8 of AGARD Report No. 349: *Glass Cockpit Operational Effectiveness.*

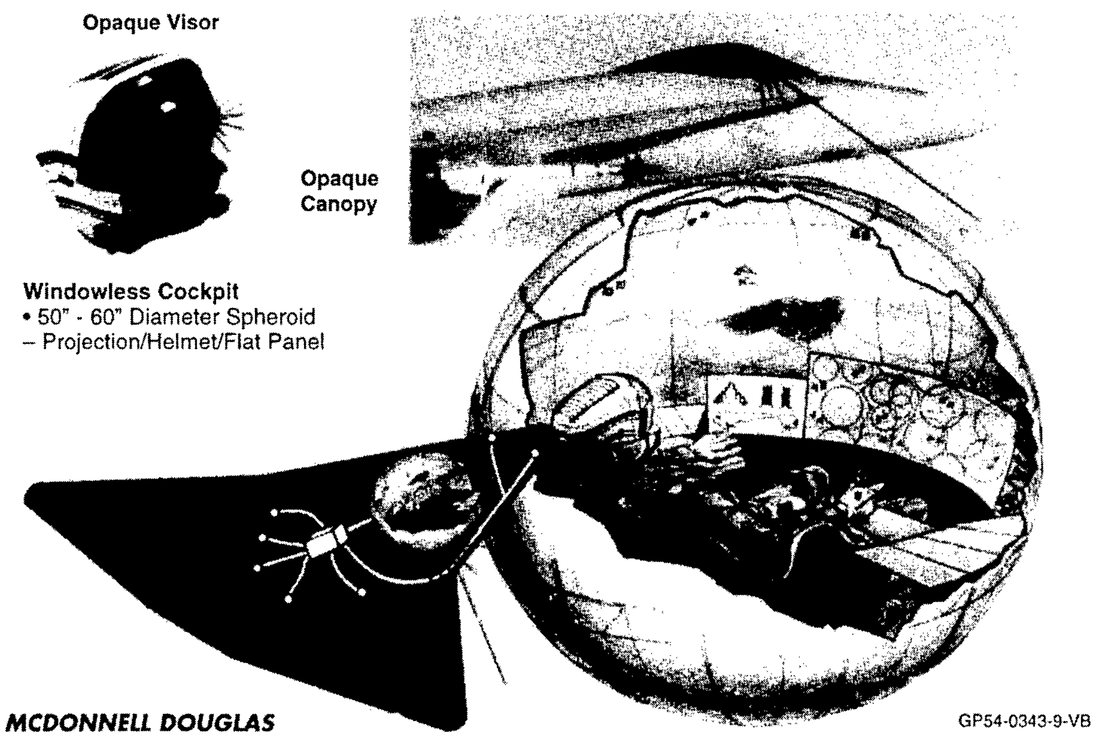

Figure 5-1: Closed Cockpit

cockpit. The helmet display could provide line-of-sight perspective views of the outside world, "through" the opaque canopy, from data bases, wide-band staring arrays, and slewable sensors. The instrument panel would, of course, be completely visible; and large displays, showing "fused" data supplemented with decision aids and expert systems would add greatly to a pilot's global and tactical situational awareness. This approach takes the middle ground technically and cost-wise, and it provides a viable solution to the laser threat problem. It also provides a "clear canopy" for training and safety if an "electronic" mechanism or structure is used to render the canopy opaque.

Because it permanently obscures the outside world, the "windowless" cockpit is the most challenging solution from all aspects: psychologically, technically, and operationally. The main element of this notional concept is an embedded 50 - 60 inch diameter dome, on which would be projected a medium-resolution "virtual world" from on-board data bases. This "virtual world" would be enhanced with real-time on/off-board sensor data. An advanced, wide-field-of-view HMD would be provided, which would overlay high-resolution data wherever the pilot looked, and very large head-down displays would provide global situation awareness. Perhaps it would help to picture this concept as a high-fidelity, domed simulator, reduced in size to fit into a combat aircraft. Although the windowless cockpit seems like an extreme approach, it does have the following advantages:

- Aircraft stealth and aeroperformance would be enormously enhanced by the absence of a canopy bump;
- Every flight could be flown "virtual VFR" (Visual Flight Rules) if the pilot desired. This virtual world would provide outstanding enhanced cognitive (visual flowfield) clues in all flight regions;
- The excellent stealth characteristics possible for this type of air vehicle design would, by reducing the need for manoeuvring, reduce the chance of pilot misorientation;
- Much of the spherical data presently displayed in cockpits on flat displays would also be available to be displayed as perspective views and at "real world" angles.

5.4 Summary

In the future, the issue of human-machine interface *per se* may become less important, as the two will be merged into unified, stand-alone systems in which the whole is greater than the sum of its parts. Enabling control and display technologies will remove constraints previously imposed by limitations of human physiology and human-machine interfaces, allowing system performance to approach its theoretical limits. Operators will appear to occupy multi-sensory, geometrically defined electronic workspaces that behave as a cooperative partner. Dialogue with the system will be based on user-state sensing, knowledge-based techniques, and inputs from the user.

Realisation of such a complete and seamless integration of human and machine (rather than through interfaces as they exist today, or the next generation of "virtual reality") will be based upon new technologies deriving from inter-related scientific and engineering advances. The relevant disciplines span cognitive neurosciences, multi-sensory integration modelling, non-linear dynamic modelling, affect and attentional modelling, and cooperative structures modelling. Engineering advances will include methods of improving haptic (by touch) communication, perceptual fidelity, and management of system latencies. Scientific advances will include the establishment of principles for:

- Moderating users' attention and perspective;
- Inferring users' emotional and intellectual state and intentions from biopotentials and behavioural expressions;
- Forming adaptive and cooperative structures optimised for the individual operator;
- Understanding the relationship between multi-sensory fusion and single channel performance;
- Exploring potential user/environment interactions that at present result in motion-induced side effects (e.g., cybersickness);
- The dynamics of implicit communication and coordination.

With effective fatigue management strategies in place, crews will maintain their stations longer, and with better results. Monitoring and intervention techniques will result in better vigilance for longer periods of time, and a reduction in the number of mishaps. Rudimentary fatigue management programmes that incorporate all of these techniques are already available; efforts to improve these techniques could be pursued cooperatively.

The human-machine interface of the future will be a partnership. This partnership will reduce the number and intensity of tasks which require human contributions. It will adapt itself to human biorhythms, and it will make possible extended operations beyond today's limitations. The operator will remain fully conscious of the environment, possibly with the aid of various intervention techniques to support sustained operations. The operator will continue to maintain authority over system functions.

6. DETECTION AND DENIAL

In the 21st century, surveillance and reconnaissance, as well as exploration, environmental sensing, information collection, research, intelligence, navigation, command and control, and communication will be essential for achieving the "high ground" in information dominance, conflict management, and warfighting.

Real-time RSTA will provide situation awareness in order to define the threat and permit real-time targeting. A 24-hour, all-weather, uninterrupted flow of information on hostile and/or potentially hostile forces and their behaviour, together with information on friendly forces, will be needed to support decision makers at all levels. Real-time links between sensor and "shooter" to support "one shot, one kill" weapon technology, will also be needed to support acceptably "quick wars," with high operational tempos, minimal friendly casualties, and low collateral damage.

Within the next 25 years, sensing capabilities will have developed to the point where accurate identification of any target, day and night, under virtually any climatic conditions, is possible. These sensing capabilities will make the concealment of military formations and major weapons systems almost impossible. In combination with the information management advances discussed in Chapter 4, this will significantly reduce any force's capability to use the element of surprise.

Two major options will remain: the "low-tech" option will be to conceal forces by having them blend into a civilian background; the "high-tech" option will be to employ a variety of active and passive countermeasures, ranging from jamming, to direct attack of the sensors, to the employment of low observability "stealth" platforms.

6.1 Sensors

The accuracy, flexibility, and resolution of passive and active sensors are constantly increasing. This quantitative evolution is leading toward a qualitative change. As an example, Figure 6-1 shows an all-weather, passive image taken from a millimetre-wave synthetic aperture radar. Such resolutions are presently available at short ranges after long duration measurements. By 2020, they should be available at medium ranges in near real time. Three of the most promising sensor developments are:

- Synthetic Aperture Radar: Imaging microwave sensors mounted onboard a moving platform, they make use of extensive Doppler processing for angular analysis of radar returns;
- Microwave Radiometry: High sensitivity receivers that can measure the thermal emissions of the objects within the main lobe of the scanning antenna;
- Multispectral/Hyperspectral Radar: An imaging sensor with the ability to perform high-resolution spectral analysis within each pixel.

Other subjects that are vital for successful design and use of RSTA sensors are discussed in detail in the Annexes: propagation, scattering, and modelling, are discussed in Annex 3; and particular signal processing developments are discussed in Annex 4.

Synthetic Aperture Radar

Airborne, as well as spaceborne, synthetic aperture radar (SAR) is largely unaffected by weather. It has day and night capability, as well as the ability to penetrate into foliage, vegetation, dry soil, and even to sense, to some extent, through shallow sea water.

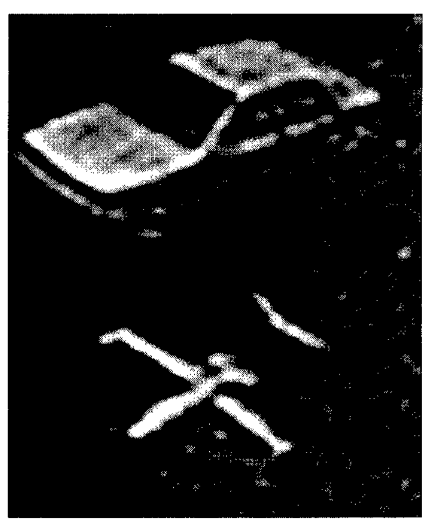

Figure 6-1: MM-wave SAR Image (short-range)

Multifrequency systems with polarimetry and interferometry are available. Large bandwidth systems, in principle, have very high resolution (dm-range). In addition to the regular strip-mapping mode, new techniques like ScanSAR and Spotlight SAR are realisable. Due to the miniaturisation of microwave and electronic components and sub-systems, SAR systems can now be designed to fit on small aircraft such as single-engine survey aircraft, RPVs, or UAVs. The bottleneck, however, is the tremendous amount of data produced, especially during large area observation with high resolution. Most of the present systems use off-line processing. The limited bandwidth of today's antenna systems also limits the resolution.

Rapid developments in digital signal processing circuits, as well as the use of new techniques and technologies like neural networks and transputer technology, together with data compression, et cetera, will make operational real-time on-board feature processing, and real-time transmission to ground stations, possible.

High-temperature superconductors will be applicable for extremely compact filtering, as well as for transmit-receive modules with high signal-to-noise ratio. Electro-optical processing devices will enable fast hybrid processing with calibration capability. Super-wideband antennas (up to 2 octaves) will yield super resolutions (cm range) over relatively wide swaths. Progress in time synchronisation, to nanosecond accuracies via airborne, spaceborne and ground-based networks, is expected. The efficiency of solid-state transmitter devices will exceed 60%. Further dramatic mass and volume reductions of microwave and electronic devices are expected. Significant progress can also be expected in the following fields:

- Design of radiating arrays: Antenna technology / Antenna measurement techniques / Antenna CAD-methods / Conformal Arrays;
- Front-end technology: Transmit/Receive Modules / Subarrays / Networks;
- Antenna calibration: Polarimetric antenna performance measurement / Near Field-Far Field measurement techniques / Calibration algorithms;
- Beamforming: Algorithms / Processor architectures / Physical pattern synthesis / Digital beamforming for antenna system-performance demonstration;
- System simulation: Optimisation of critical physical performance parameters.

A forecast of the time scale for this evolution is found in Table 6-1.

Detection systems employing a network of many receivers installed in different flight vehicles, and using one common airborne, spaceborne, or ground-based transmitter, will be available. Such networks will combine the advantages of the receivers' silent operation, the accuracy of monostatic radar, and the reduced vulnerability of a distributed computer network. Each SAR will produce its own Digital Elevation Model, and sub-clutter visibility will be increased dramatically by the use of coherence and entropy techniques.

2000	2005	2010-2015	2020
• Real-time on-board processing operational	• Feature processing operational • Mass and volume reduction of information processing electronics: Factor 10 • Conformal arrays and super-wideband antennas • High-temperature super conductors available operationally	• Real-time feature processing (dependent on target complexity	• Mass and volume reduction of information processing electronics: Factor 100

Table 6-1: Evolution in Sensor Systems

Further progress in miniaturisation will make SAR available for terminal guidance purposes as well as for intelligent ammunition. SAR could also be installed within the tips of helicopter rotor blades. The high degree of automation could make it possible to design high-resolution SAR, with high-target positioning capability, for unmanned vehicles. Today's experimental techniques for MTI will be operational. New methods for calibration and error elimination will neutralise many of the negative influences of atmospheric, tropospheric, and ionospheric turbulence, resulting in an increase in resolution power, image quality, and measurement accuracy, as well as in interferometry applicability. Additionally, it will create the possibility of new frequencies for spaceborne and airborne SAR. Frequencies significantly below 1 GHz in spaceborne SAR will increase the capability to penetrate vegetation, as well as dry surfaces.

Microwave Radiometry

Microwave radiometers are very suitable sensors for high-quality, short-range imaging systems. They collect object contours, and target shape and composition better than radar, and are nearly independent of ambient illumination and weather conditions. Using this technique, metallic targets have high contrast against nearly all earth surface backgrounds. Compared to active systems, the passive and silent microwave radiometry technique uses low data rates, which makes this technique well-suited for short range RSTA systems. For target acquisition, imaging radiometry systems can be used in aircraft, unmanned vehicles, and for terminal guidance in missiles.

The total frequency range presently used for microwave radiometry, remote sensing, and earth observation applications extends from approximately 300 MHz to 300 GHz. The frequencies mainly used are 35 GHz and 90 GHz, where there are windows of low atmospheric attenuation. Higher frequencies (140 GHz) are on the brink of operation. The radiometric resolution that can be reached is about 0.1°K for 1 ms integration time. Millimetre-wave radiometers use real antenna apertures, leading to the principal disadvantage of poor spatial resolution. Imaging systems use scanning antennas, mainly swinging or rotating mirrors; the angular resolution depends on the space available within the carrier platform for the antenna system. The radiometric resolution responsible for the contrast depends on the noise figure of the receiver. At frequencies < 40 GHz, amplifiers with about 300 °K are available for uncooled systems. This is sufficient for look down observations where the targets are in a natural environment (about 300 °K surrounding temperature). Some 10 °K can be reached with cooled systems. In the frequency range between 40 GHz and 150 GHz, superheterodyne receivers have noise temperatures of about 1000 °K in the uncooled case, and about 300 °K in the case of cooling.

Presently, an aperture synthesis technique is under consideration for the increase of spatial resolution. Some experimental systems of this type, where mechanical beam movement is not necessary, exist. In principle, aperture sizes on the order of the dimensions of the carrier platform can be used, which leads to a dramatic increase of geometric resolution. However, this method calls for matrices of many small single-receiver elements, and also requires time-consuming correlation processes.

New components currently under development that use High-Electron Mobility Transistors (HEMT), Josephson Junctions, and High-Temperature Super Conductors promise low noise temperatures. Low noise integrated front-ends, including antenna elements, pre-amplification, mixing, and post amplification, with low volume and weight and at low cost, will be developed. The development of target recognition and classification algorithms will be increased, especially focusing on the use of lightweight, fast computer electronics and comprehensive data bases.

Due to their relative ease of construction and use, real aperture systems will remain the dominant imaging systems for the next decade - when spatial resolution is not the dominant design goal. Otherwise, aperture synthesis systems will be developed with special attention to the number and placement of the antenna elements, and to the reconstruction algorithm (constraints imposed by the sampling theorem). Additionally, aperture synthesis extends the range to longer distances, because of the possible higher spatial resolution, and offers the possibility to get microwave images of near-optical quality.

Multispectral and Hyperspectral Sensors

Remote image sensing is receiving a tremendous amount of attention, both in military and civilian

communities. The intention of this section is to briefly describe the current state-of-the-art, and to highlight some of the more innovative concepts which lead into the future. Imaging capabilities are not discussed, other than to note that they will need to be replaced or upgraded to meet the needs of NATO in 2020. The technologies and applications discussed below pave the way for these improvements.

Multispectral imaging (MSI) provides spatial and spectral information. MSI is currently the most widely used method of imaging spectrometry. The US-developed LANDSAT, the French SPOT, and the Russian ALMAZ are all examples of civil/commercial multispectral satellite systems. These systems operate in multiple bands, can provide ground resolution on the order of ten metres, and support multiple applications. Military applications of multispectral imaging abound. The NATO armies are busily incorporating MSI into their geographic information systems for intelligence preparation of the battlefield, or "terrain categorisation" (TERCATS). MSI data can be used to help determine "go, no-go, and slow-go" areas for enemy and friendly ground movements. By eliminating untrafficable areas, this information can be especially useful in tracking relocatable targets, such as mobile short range and intermediate range ballistic missile launchers.

MSI can also be used for near-shore bathymetry, detecting water depths of uncharted waterways, to support amphibious landings and ship navigation. Using MSI data in the radar, Infra-Red (IR), and optical bands, identification of environmental damage caused by combat (or by natural disasters) can be more quickly discerned. For example, LANDSAT imagery helped determine the extent of damage caused by Iraqi-set oil fires in Kuwait during the Gulf War.

Although MSI has a variety of uses, and many advantages, this sensing technique results in a decrease of both bandwidth and resolution from conventional spectrometry. Additionally, multispectral systems cannot produce contiguous spectral and spatial information. These disadvantages must be overcome to meet the surveillance and reconnaissance needs of the warfighter and commander of 2020.

One promising technology for overcoming these shortfalls is hyperspectral sensing. Hyperspectral devices can simultaneously produce thousands of contiguous spatial and spectral elements of information. They make use of a very large number of spectral bands, providing more complete information on the physical characteristics of the observed object, resulting in a higher certainty of object identification. Although hyperspectral models do exist, none has been optimised for missions from space, nor integrated with the current electro-optical, infra-red, and radar imaging technologies. This same technology can be equally effective for ground target identification. Hyperspectral sensing can use all portions of the spectrum to scan a target or object, collect bits of information from each band, and fuse the information to develop a signature of the target or object. Since only a small amount of information may be available in various bands of the spectrum (some bands may not produce any information), the process of fusing the information and comparing it to other intelligence and information sources becomes crucial.

Adaptive hyperspectral detection technology that will be realised in the next decade will dramatically enhance the ability of electro-optical sensor systems to detect and track theatre ballistic missiles, cruise missiles, and aircraft threats, as well as to perform technical intelligence missions. The concept of an adaptive hyperspectral sensor system is to combine hyperspectral detection with knowledge-based, "smart," signal processing. Advanced atmospheric background and target models are used to adaptively match a sensor system's bandpass, threshold, and other operating parameters to the immediate viewing conditions, so as to fully maximise the target signature gain and minimise the clutter in the viewed scene.

The development of adaptive hyperspectral detection techniques will exploit the unique virtues of fusing spectral and spatial data from many bands. It will achieve levels of detection and tracking performance that greatly exceed those currently available, which use only one or two independent bands.

The combination of several new emerging technologies in an adaptive hyperspectral discriminator represents an entirely new approach to designing sensors for surveillance, reconnaissance, and intelligence missions. The development of advanced tuneable filters, focal planes, and cryocoolers will enable the acquisition of spectral and spatial data in multiple bands nearly simultaneously. These innovations in optical instrumentation are envisioned to be made

even more powerful by enabling technologies derived from the development of high-performance, lightweight signal processors.

Signal processing techniques based on Artificial Intelligence, neural networks, and other technologies will provide a feedback loop to adaptively tune a sensor system to locate, identify, and track a number of different classes of targets that currently require different spectral bands to optimise the system for each class of target and target-background signature. When incorporated in multiple stereo-viewing satellite, and/or aircraft, and/or UAV platforms, this technology, combined with new data fusion techniques, will provide extremely accurate data on target type and trajectory.

Integral to the implementation of advanced adaptive signal processing and multi-source data fusion techniques will be the development of new, highly robust, high-fidelity dynamic and statistical models of atmospheric and hard earth spatially and temporally structured radiance backgrounds for adaptive target detection in clutter. In addition, these techniques will be dependent on highly accurate time/space positioning data.

The payoff to be realised from adaptive hyperspectral sensor technology is the capability to conduct technical intelligence, early warning, and tactical missions using a single electro-optical sensor system. The adaptive feedback of the hyperspectral sensor will enable a satellite system to change almost instantaneously, for example, from a ground-viewing mode for technical intelligence gathering to a limb-viewing mode for target tracking.

In addition to providing earlier reporting of threats and improved threat track accuracy, this new technology will enable sensor systems to operate in regions of high noise, in which current fixed bandpass systems are not functional, in order to verify whether or not likely target detections are real. This will significantly reduce the number of false and missed targets.

Distributed Sensor Systems

It will also become possible to use very large numbers of small, cheap sensors, instead of a small number of (relatively) large and complex sensors.

The following advances will support this capability:

- System miniaturisation - especially miniaturisation of sensors and sensor electronics;
- Multiplicity and variety of systems in use (miniaturisation is an influential factor: it is easy to implement several small sensors on a unique platform);
- Capability to transmit a larger quantity of information to a larger number of operational users;
- Development of algorithms for multi-source information correlation and fusion.

Tiny, low-cost sensors in the air, in space, or on the ground might be deployed by the hundreds or thousands, forming a network that could beam a composite image of an unfolding situation. As such systems as the Advanced Warning and Control System (AWACS) or the Joint Surveillance Target-Attack Radar System (JSTARS) become increasingly vulnerable, the RSTA mission, at least in early stages of a conflict, is likely to move towards robotic warfare. The reconnaissance and targeting role will increasingly be taken over by unpiloted aircraft - highly novel versions of those flown during Desert Storm - and large numbers of minute craft could collectively act as battle surveyors.

"Multi-sensor" capability, combining inputs from a variety of sensors, is another critical concept. The developing domain of "data fusion" will expand our present exploitation of the electromagnetic spectrum to encompass more "exotic" sensing technologies. Future perception systems will, therefore, collect and fuse data from many sensory inputs (optical, infra-red, multispectral, tactile, acoustical, laser radar, millimetre-wave radar, x-ray, et cetera) to create a structural multi-sensory signature of an acquired object (buildings, airborne aircraft, people, aerosol clouds, and others). Objects will be identified by comparing their structural sensory signatures against a pre-loaded data base in order to identify matches or changes in the structure, for identification or comparison. The overall system would accumulate sensing data from a variety of sources, such as space-based multispectral sensors, UAVs, platforms such as AWACS, weather balloons, probes, land radar, ground sensors, ships, submarines, surface and sub-surface sound surveillance systems, human sources, et cetera. Smart sensor management systems will allow for automatic adaptation to

changes in mission requirements and environment. This is a prerequisite for UAVs and unmanned tactical aircraft (UTA).

It is expected that the most significant technological development leading to change will be found in the areas of sensor signal processing, and fully automated exploitation (including automated classification) of data provided by various sensors through their fusion, correlation, and the application of artificial intelligence techniques. Technological developments will be applied to space-based and in-situ systems with extremely high spatial resolution.

Due to the expected increase in computer power and network communications bandwidths, significant progress can also be expected in the following fields:

- Passive or active automatic calibration of multiple sensors;
- Data association and estimation techniques, through the use of efficient hardware implementations of algorithms;
- Symbolic reasoning, through the use of large-scale blackboards and/or associative memories;
- Sub-symbolic to symbolic interface.

Selection of the specific sensor employed is highly context dependent, as is the selection of the optimal combining algorithm. The basis of fusing information is well established - leading from least squares estimates through maximum likelihood to the sequential estimate techniques, e.g., Kalman filter. Development is not constrained to the military, and many commercial applications are relevant.

It is anticipated that cost will be driven down as COTS software becomes readily available. Current algorithms, particularly for plot extraction, achieve high performance, but at the expense of massive computing power. The rapid development in processors is likely to continue, and the data fusion domain will profit as a result.

The general topic of multi-sensor data fusion is popular, as evidenced by the profusion of research papers. Many and varied methods of data fusion are under review, e.g., using numeric and symbolic methods. However, no mathematically rigorous methods have emerged with researchers developing conceptual frameworks.

Combining data from multi-wavelength sensors at spatially diverse locations constitutes an important approach to counteracting target stealth. State-of-the-art fusion algorithms use plot level data to achieve highest performance. The algorithms require massive computing power and calibrated sensor performance models of great detail. Progress will be made toward better models and self-calibration to account for performance changes during the sensor's operational life. Once individual observations have been associated with a particular target, a synthetic observation of higher quality is obtained by mathematical means - including artificial intelligence methods.

Data fusion for the generation of synthetic imagery from data of individual imaging sensors will be the final step in this process. Real-time data fusion from non-collocated sensors will require robust, high data-rate inter-sensor communications.

6.2 Anti-Stealth Technologies - Advanced Sensors

Detection of future stealthy platforms will require the use of more subtle target signatures and an expanded set of measurement parameters. It will entail the need to combine information from a variety of different sensors. Among the sensor approaches that will contribute in this regard are the use of very high resolution (which increases the target to background contrast, discriminates against enemy interference, and potentially distinguishes target substructure) and multi-frequency, multi-static radar.

Ultra-Wideband Waveforms

At this time, ultra-wideband (UWB) systems are experimental, proof-of-concept, or instrumentation radars. However, they will become valuable assets in detecting covert tactical targets. The term ultra-wideband generally applies to radars with 25% relative bandwidth or more. Specifically, it refers to systems at wavelengths longer than low microwaves. A unique advantage of radars operating at longer wavelengths is their ability to penetrate layers of camouflage, such as foliage, earth, or man-made, non-metallic structures, with tolerable attenuation. To retain sufficient resolution, ultra-wide relative bandwidths have to be employed.

Detection is based both on target resonances and on the resolution of target substructure characteristics. Competing clutter originates from target-size cells or smaller. Advanced pulse transmitters with high peak power will become available, with pulse repetition rates limited by range ambiguity only. Wideband-modulated coherent continuous-wave sources achieve comparable performance. Receivers with instantaneous bandwidths of several gigahertz allow time domain and frequency domain processing. They will not be noise limited in extracting target information from the received signal. Array or reflector antennas of practical size will have usable directional patterns; that is, single or multiple beams with low grating lobes for target angular resolution. The problem of increased UWB data volume will be handled through the use of ultra-high speed or parallel processing computers.

6.3 Stealth Technologies

Passive Methods of RCS Reduction

Reducing the radar cross-section (RCS) by shaping of the airframe/engine inlets, in order to redirect scattered energy away from the radar's direction, is the preferred technique to reduce detectability. At microwave frequencies, airborne targets are up to thousands of wavelengths in size. Design for optimal reduction in RCS can only be achieved by detailed computer modelling. To model a full-size target with sufficient realism, its surface must be represented by a composite of up to millions of individual elementary facets. Drastic increases in speed and power of computation will facilitate a precise determination of the simulated scattering behaviour of targets, covering the metric to centimetric wavelength range.

Stealth against a monostatic radar requires that energy impinging on the target be redirected outside of a limited forward threat sector centred on the sensor. Multi-static sensors aggravate the situation. One option to minimise detection by multistatic sensors is to concentrate scattered energy into a limited number of narrow, intense, spatially distributed beams. Such shaping tends to compromise the aerodynamic properties of an airborne platform. This, in turn, increases the dependence on automated flight control systems.

The radar signature of target structures that are not amenable to shaping can be reduced by radar absorbent coatings. While shaping carries aerodynamic penalties, absorbers impact weight and maintainability. Current resonant absorber technology will be ineffective against future wideband radar.

However, new materials research will lead to broadband absorbers to counter the wideband radar threat. Such materials will need to provide a good match, over a wide wavelength range, so that most of the radar energy enters the absorbing layer, rather than being reflected from the surface discontinuity. Once inside this layer, the energy must be absorbed within the least possible depth of absorber. This will minimise the impact of the absorber's weight and shape upon the platform's performance.

A technique that holds great promise for the future is the use of radar absorbent structures. Composite materials find increasing application in this technique. These materials are non-metallic; hence, they are inherently less reflective. They also make possible a more gradual change in absorptive properties inside the medium, as well as a more complete absorption of the radar signal. Developing such materials with the mechanical strength to withstand the stress of flight is a pre-condition for their use in future combat aircraft. It appears that growth in use of unmanned aircraft will open up a much wider field for the application of composite, radar-absorbent structures.

Finally, the time-honoured military tactic of concealing airborne targets behind terrain or vegetation will reach a greater level of perfection. Better on-board guidance will enhance vehicle concealment by permitting closer terrain following profiles. Highly resolving airborne sensors, in conjunction with rapid-response automated flight control and stand-off weaponry, will allow most of the mission to be performed outside the detection range of ground-based or low-flying enemy radars.

Active Measures of RCS Reduction

Conceptually, both passive and active cancellation techniques have long been recognised as means to reduce a target's radar echo. For active cancellation, the response from each scattering centre has to be cancelled with another signal of equal magnitude and opposite phase. In principle, this could be achieved passively for simple scattering bodies.

The complexity of real airframes, and the complexity of the required cancellation structure, makes this a forbidding task - even with the anticipated advances in modelling such designs. Active cancellation involves the generation and re-transmission of signals, such that the energy reflected by the target is nulled. A concept has been proposed where a coating that is essentially microwave transparent is attached to the surface of the airborne platform. A plurality of detector/emitter pairs contained within the coating would detect and actively cancel the incoming microwave field at each respective detector/emitter pair. Although the huge number of scattering centres on a typical airframe appears to make this task insurmountable, considerable progress is being made in miniaturisation and in very large-scale integration of microwave circuits. In view of the difficulty of any stealth improvement, this approach is very attractive. It will continue to be explored as technology matures.

A deficiency exists, particularly with regard to multi-static sensor configurations, where there is a much-reduced angular range into which to deflect the incoming radar energy. At decimetric and metric radar wavelengths, targets approach resonant size and active cancellation becomes even more desirable. Shaping and absorptive coating is almost ineffective when the airframe re-radiates according to its gross structure. Compensation of the re-radiated signal requires far fewer sources than in the microwave case.

IR Signature Reduction

When dealing with protection against short-range sensors, infra-red signature reduction must be addressed. The infra-red emission could be lowered in four areas, which are currently under study:

- Electromagnetic coatings - surface finishes with emissivity values controlled through low voltage currents;
- Thermochromatic coatings - similar to electromagnetic coatings, but emissivity is defined by the temperature;
- Electrostatic heat transfer - a mechanism to disperse the heat by electrically charging the exhaust system;
- Chemical additives - the injection of particulates in the exhaust jet to reduce or inhibit, through absorption or molecular quenching, the radiation emitted by combustion products.

Physical measures to reduce the effects of the plumes are already being applied. In the future, these will be improved by such measures as enhanced plume mixing, nozzle shaping and cycle tailoring.

The ECCM measure that is applied to modify the propagation media is the introduction of multispectral obscurants to interrupt the acquisition of the position. The basic physical processes are understood, but the dispersion systems have not been exercised in all operational conditions. An outstanding problem is to combine the different particulate materials that are effective in selected parts of the band. Some early systems, which operate in the visible and infra-red region, have been deployed.

6.4 Jamming/Anti-Jamming

If detected, disrupting the final guidance phase of an attacking enemy missile is a matter of self-preservation, particularly for an aircraft. However, when the range of the threat is increased, the use of jamming for protection becomes less favourable; it advertises position, and it is open to attack from anti-radiation missiles. Progress in jamming should improve the knowledge applied to make more efficient use of the available power, and to be selective to prevent disruption of friendly emissions. This requires an environment in which the jammer must be adaptive/reactive.

The move to closely couple an ESM sensor to the ECM function will help, but this will only be implemented in an incremental fashion.

Attempting to inject energy into a sensor will remain the principle of jamming. The crude approach is to flood the sensor domain with white gaussian noise, but this is not efficient and may prevent information from reaching friendly sensors.

Use of spread-spectrum methods requires the jammer to apply selective modulation, since the power required to cover the complete band is excessive. The use of fast frequency-hopping prevents the use of repeater jammers because of the inherent propagation delay, unless a large number of devices are distributed close to the

source. Direct-sequence modulation also provides a processing gain that must be eroded by the jammer; this can be reduced, to some extent, if the class of code generating the sequence is known, so that the jammer can emit a sequence with a high cross-correlation. In general, however, the jammer may not have the time to analyse the emitted signal, since a wide range of linear and non-linear sequences can be readily produced.

The strategy adopted is one of jamming selected bands. The response to tone and combined jammers needs to be analysed. To counter some of the effects, greater use of hybrid modulation schemes can be anticipated.

A further measure of protection against jamming can be provided by spatial discrimination achieved by nulling antennas. Developments in the design of adaptive arrays with better control of the phase at each element indicate that nulls of 30 dB or more can be steered to react to a jammer on a fast moving platform. Deeper nulls are possible with improved phase control, but a longer time is required to adapt the parameter values. The use of smart materials will allow designers to distribute the antenna elements as conformal arrays, and therefore utilise a larger percentage of the airframe.

Electromagnetic packaging will be a major contribution to success, ensuring that the mutual coupling between antenna elements is acceptable. Octave bandwidths will be available, with a potential for use of high-temperature superconducting components, e.g., low-loss antenna elements and phase shifters.

6.5 Stealth versus Anti-Stealth

The electronic arms race between sensor systems and anti-sensor systems will continue into the foreseeable future. On the one hand, the design of sensors will be continually improved - both basic performance and resistance to anti-sensor measures. On the other hand, there will be further progress in reducing the sensor-related signatures of aerospace vehicles and targets of all kinds, and improved forms of electronic countermeasures will be developed to further degrade sensor systems' performance.

Massive advances in capability for data acquisition, long-range data transfer, and data evaluation will drive sensor system improvements in the next decades. Sensors will become more capable because of improved sensitivity, agility, and resolution. These gains will be multiplied by inter-netting of sensors in both the spatial and frequency domain. Automation will play an important role in target detection, identification, and timely response.

At the same time, the detectability of airborne weapons systems will be reduced. Their observable radar and infra-red characteristics will be reduced through the use of novel materials, and through advanced designs made possible by advances in aerodynamics, propulsion, and automatic flight control that ensures the flyability of highly optimised stealth platform designs. In addition to target structural characteristics, the signals radiated by on-board navigation, communication, and weapons delivery systems are contributors to vehicle signature. Their detectability will be reduced by many of the same technological refinements to be incorporated into the opposing sensors. Better on-board guidance will further reduce vehicle exposure by permitting closer terrain following flight profiles.

6.6 Summary

In future conflicts, where stealth and anti-stealth technologies compete, the better technologically equipped force will hold a distinct advantage. Presently, stealthy air vehicles achieve only relative invisibility against modern sensors. Tactics and countermeasures must also be employed to reach an equilibrium in the electronic battle.

During the coming decades, the stealth versus anti-stealth competition will be propelled to higher levels of sophistication by major technological advances. Regardless of the magnitude of technological progress, neither side will gain a decisive advantage - simply because technology gains in each individual category can be exploited by both sides to comparable effect.

Although the design and development of anti-stealth systems will be expensive, the cost of re-engineering existing stealthly platforms, or of producing new ones, will normally be far greater. Thus, even if it is technologically possible to react to new anti-stealth systems, it may not be economically feasible to respond quickly - or at all - to each new threat. Such response limitations could create windows of vulnerability for future forces.

Anti-jam performance, with improved processing and components with shorter time constants, will mirror the advances made in jammers. To maintain the advantage, a transmission mode, resistant to enemy counter-actions, must be held "in reserve". This mode must come as a surprise initially; it could prove decisive during the time required for the enemy to design an effective countermeasure.

Since many of the ingredients of future detection and denial systems will not have low-cost commercial equivalents, the advantage in detection and denial will be resource driven.

7. EVOLVING SYSTEMS

The military systems in use today will continue to evolve. Some concepts, such as the UAV and heavy-lift aircraft, will evolve along a variety of paths. Others, such as the next generation of fighters, will develop incrementally along a quite predictable path. Directed-energy weapons will evolve into commonly used weaponry by 2020.

This chapter discusses the evolution of the following systems:

- **Directed-Energy Weapons**: Progress in the development of very high-power generators and projectors of electromagnetic wave energy - both radio frequency and optical - holds out the prospect of significant new capabilities in both offence and defence. It also creates new threats;
- **Future Combat Aircraft:** Primarily the fixed-wing fighter;
- **Future Heavy Lift:** The development of very large transport aircraft, having very long range and flight duration capabilities, opens up new possibilities for military applications;
- **Future UAVs:** The capabilities of long-range/long-endurance drones will have a profound effect on operational and support requirements. In addition, progress in micro-circuitry and miniaturisation will make possible vehicles the size of a large bird, which will have a small, but capable, payload for reconnaissance and/or attack.

7.1 Directed-Energy Weapons

As a potential source of damage or injury, directed-energy may be the product of a high-power generator conceived and designed for use as a damaging weapon, or it may be the incidental result of energy transmission for a quite different purpose (usually sensing or communication). This section provides a brief review of the range of high-power threats, and of the threat to electro-optic sensors and human vision[1] posed by the ubiquitous low-power laser sources used for range finding, target designation, and communication. The end of the section presents technologies which can assist in providing protection against the low-power laser hazard.

Directed-energy weapons can provide any commander with the particular benefit that an effective, but non-lethal, option can be applied. The capability of defeating command and control systems or air defence systems without overt lethal force has considerable merit. The next stage, in which damage can be achieved with devices which are non-attributable, is also a possibility. The history of directed-energy weapons is extensive, but the concept has not been implemented successfully until the last few years, when it has gained increased prominence. The value of research in this area derives from evidence of damage to electronically rich systems, increased use of electronics in mission-critical applications, and development in radiation source technologies in both High-Power Microwaves and Lasers.

The topic of directed-energy weapons covers a wide set of disciplines, with research carried out across a broad front, in different areas. The technology issues, military applications, and proliferation possibilities for the following four categories are discussed below:

- Electromagnetic and Ultra-Wide Band,
- Pulse Systems (EMP & UWB),
- High-Power Microwaves (HPM),
- Radio Frequency Munitions, explosively driven (RFM),
- Laser-Directed Energy.

Electromagnetic Pulse and Ultra-Wide Band Pulse

This class of device produces a high-power pulse covering the HF to the UHF band. An effect similar to an exoatmospheric nuclear blast is created. However, in this instance the pulse is generated by non-nuclear means. The disruptive aspect is that the victim system absorbs power. This can occur if its physical dimensions are of the order of a few metres and react to the incident electromagnetic wave. The technology invoked is relatively simple but requires some intricate design detail. Widespread availability can be anticipated.

[1] See also Chapter 5 and Annex 7.

Ultra-wideband devices produce a continuous spectrum of pulsed energy, from 100 MHz to 5 GHz, with the power present at all frequencies simultaneously. This is produced by generating a very fast, relatively narrow pulse, with rise and fall times on the order of 10 picoseconds. Several devices can switch in this time, including transmission lines loaded with ferrite magnetic material, laser-triggered bulk semiconductor switches, avalanche transistors, and superconducting devices. The accurate control of the switch permits each element to be combined in a phased array, which can then create beams with spatial spread less than one degree. The wide bandwidth increases the probability of coupling with a number of different features on the target, but the amplitude of the coupled signal might be modest. However, if the power is absorbed by a semiconductor device junction, in a time scale which is too short for the resultant heating to diffuse away from the substrate, the device could suffer damage.

High-Power Microwaves

High-power microwaves can be employed to disrupt the electronic components of many sophisticated military systems. The trend to introduce more technology decreases the susceptibility threshold, and thus exposes the systems to lower power devices, or increases the range at which sources with a defined output are disruptive. Key elements for high-power microwaves to be effective are the carrier frequency and the modulation. At low power density, sensors are confused; burn-up of electronic components is achieved at the higher power levels. Three sources are considered in greater detail: the Travelling Wave Tube (TWT), the Magnetron and the High-Power Klystron.

Travelling Wave Tubes. The advantage of the travelling wave tube is that limited frequency agility can be achieved. However, this advantage is offset by the reduced power output available. A state-of-the-art, coupled-cavity TWT in L-band can produce cW power at 12 kW, which is much lower than desired. By comparison, pulsed tubes have produced peak powers up to 150 kW. Development in this area on a 'Pasotron' tube has shown the device to be capable of producing usable power output, but with low efficiency; it will thus require extensive cooling.

Magnetrons. Magnetrons are considered in this context because of their maturity and relatively high efficiency. However, they are inherently limited to a mean output of 100 kW in L-band. Several high-power magnetrons are available in L-band, ranging from several megawatts output with a duty factor of 0.001, through to one gigawatt with short pulses of duration 100 ns. Again, cW power output is low, as anticipated, with measurements in the tens of kilowatt range. The research in improving these devices continues, with an indication that tunability may be possible.

The cause of the inherent limitation is the physical structure, since the electron emission, RF interaction, and beam collection process all occur in the interaction space between the anode block and cathode. Back bombardment of the electron cloud into the cathode causes an insurmountable problem at high-average power, while deposition of electron energy onto the fragile RF circuit causes gas evolution in the regions of highest electric field strength. Subsequent gas ionisation, electric field arcs, and even melting of the anode vanes can occur.

Klystrons. In contrast to the magnetron, the physical structure of the klystron permits higher powers; they are, however, long and heavy. The tube, together with the ancillary services, may amount to several tonnes. Current klystron amplifiers satisfy the nominal specification. Specific tubes manufactured in the US can produce 2 mW peak at 1 GHz, with a duty factor of 0.125. A French tube is quoted with an output of 10 mW of peak power, with a second tube from the same manufacturer giving an output of 1 mW in a cW mode.

The beam within the klystron is generated in a gun region, bunches as it drifts, generates power when it interacts with the output cavities, and is collected in a separate beam collector. With this configuration, klystrons exhibit the highest reliability figures of current high-power tubes. A negative feature is that they have limited tuning ability.

Evolution. Work on the 'Super-Reltron' tube will continue to attempt to marry the high-power attributes of the klystron with the size and efficiency of the magnetron. Laboratory models of the high peak-power tube have achieved hundreds of megawatts of power at L-band, with an efficiency approaching 50%. The tuning achieved has been 7.5% about the nominal centre frequency, but with a modification to the tuning

geometry, it is expected that this figure could rise to 15%. The same technology can be adapted to generate high peak power at other frequencies, with 50 mW reported at 1.3 GHz and 10 mW at 2.8 GHz.

In the longer time frame, we can anticipate that 3 gW of peak power will be produced in the range 1-10 GHz, with the peak power falling to tens of megawatts at 35 GHz. The efficiency will be low, with cooled electromagnets and flowing insulating oil adding to the mass. The output from the amplifiers can be fed to high-gain antennas to produce pencil beams necessary to reduce the effects on co-located equipment (or "fratricide effects"). The limited tuning ability will remain a problem that limits the capability to attack targets which may have diverse susceptible frequencies.

System Considerations. For integrating such sources into a defensive system (against attacking aircraft or missiles), or even an offensive one (against satellites from the ground, against various targets from an airborne platform), specific attention has to be paid to the designation, beaming, and kill assessment aspects. They may result in different technological needs, depending mostly on the operational range that is required. One of the critical technologies seems to be large-phased arrays with high peak-power handling capability. Active arrays are possible solutions, where the very large peak-power transmitter is replaced by many smaller synchronised transmitters; some of the sources discussed above may be adequately synchronised for such operation.

Hostile Exploitation and Proliferation Aspects. Some nations of the former Warsaw Pact are known to have pioneered various technologies involved in HPM and related directed-energy weapons; proliferation risks have to be considered.

Techniques for hardening sensitive electronics against such threats exist and are likely to be improved in the future. High-temperature superconductors are one of the technologies which might offer protection without sacrificing performance. There will be a cost penalty on hardening electronics.

RF Warheads

Replacing the warhead of a missile or artillery shell by a high peak-power RF radiating device may prove very effective against various (including high-value) targets, whose electronic circuits might be highly vulnerable if they are engaged at short distance. Combinations of explosive devices, magnetic coils, microwave generators, and antennas are keys for designing such warheads.

Laser-Directed Energy

There are considerable potential benefits of applying high-power lasers as weapons, particularly the very short time of flight coupled to a highly directional beam. Medium-power lasers capable of causing physical damage to sensors are within reach of a large number of countries, but exploitation demands very high accuracy in the pointing and tracking functions. It is also important that the wavelength of the source is within the passband of the sensor. Full laser damage weapon technology, in which the delivered power is sufficient to vaporise elements of the target structure, e.g., a radome, is currently restricted to a small number of countries.

High-Energy Laser (HEL). The concept of employing HEL systems as directed-energy weapons is at least a quarter of a century old. Until recently, problems of size and weight have proven insurmountable, but it appears that the next quarter century will witness major breakthroughs, particularly in aerospace applications for HEL weapons.

The first step will be taken in the very near future by the USAF Airborne Laser (ABL) programme. This programme, mounting a Carbon Oxygen Iodine Laser (COIL) on a large transport aircraft operating above 40,000 feet MSL, is expected to achieve a weapons quality beam sufficient to destroy ballistic missiles in the boost phase. It is anticipated that similar systems will be developed for surface-to-air and surface-to-space lasers, building on experience gained from the ABL programme.

The technological drive to go beyond ABL will focus on reducing the size and weight penalty, with the eventual goal of integrating HEL weapons with the full array of future air combat systems. The first applications are expected to be lightweight (relative to total payload) lasers for active self-defence of large aircraft against incoming missiles/rockets. Sensor blinding for this purpose should be realised in the short term. High-energy attack on the incoming missile itself should be possible by 2020. A larger system,

designed primarily for air-to-air combat, could also be developed with a sustained effort. The primary technological focus required is in the field of Diode-Pumped Solid-State Lasers. The challenges include improving diode and diode-laser efficiency, phase conjugation to improve beam quality, and improved thermal management. All of these improvements should serve to reduce the size and weight of the system, as well as the cost.

Work toward the realisation of a fighter/attack-type aircraft employing HEL as its primary weapon system has already begun. Such a system would make use of a phased array of diode lasers embedded in the skin of the aircraft. This concept will take advantage of High-Power Semiconductor Laser technology, and will require advanced control techniques to combine thousands of individual lasers into a coherent beam sufficient for use as a weapon. Such a system is not foreseeable within the timeframe of this study.

Low-Power Laser Threats. Low-power lasers are increasingly used, in both the military and civil domains, for purposes such as range finding, target designation, LIDAR, public entertainment, et cetera. They are readily available from diverse commercial sources. Lasers specifically suited for counter application, such as multiwavelength or agile lasers, are expected in large numbers. Many of these lasers are, or will be, capable of dazzling or destroying sensitive electro-optical sensing devices, as well as human vision. There have already been incidents of entertainment lasers causing problems for airline flight crews. In the hands of hostile forces, low-power lasers can constitute a potential threat to NATO forces and civil activities.

Dazzling and reversible or irreversible blinding of personnel, or of the windows/sensors of an airborne vehicle, caused by low-power laser radiation will produce effects ranging from abandonment of the mission to platform damage - possibly including the permanent blinding or death of personnel.

There are several ways in which laser radiation can affect the human visual system. Physical damage of the eye can cause irreversible blinding. Disruption of the visual function can occur through non-damaging mechanisms. Laser-induced glare, or light adaptation, reduces the visible function by temporarily reducing the sensitivity of the eye to light (flash blindness). Light scattered in the aircraft canopy decreases the apparent contrast to the air crew. Bright light sources in the field of view divert the attention from important tasks. Higher energy radiation may cause loss of clarity in aircraft transparencies.

Experiments have shown that the probability of target detection, as a function of search time under flash conditions, is statistically reduced, equivalent to an increase in acquisition time from 2 - 12 times, depending on the environmental and flash conditions.

All of these effects will result in reduced aircrew performance with respect to navigation, reconnaissance, target acquisition, and weapons delivery. They will also reduce the performance of autonomous systems dependent upon electro-optic sensors. If sensors are used to augment or to replace human capabilities, the hardening of these sensors against laser radiation is extremely important.

Aside from the ethical arguments against blinding a human being, the application of lasers of this type may not seem to be very effective from the perspective of well-developed Western forces. From other points of view - of terrorists, small-scale paramilitary, or military forces based on totally different doctrines - counter and blinding lasers are, and will be, of high value. The potential psychological impacts of their application is significant.

The United Nations, including member countries of NATO, is trying to derive an *INTERNATIONAL BAN OF BLINDING LASERS* (Vienna 1995/96). However, it will still be necessary to ensure the availability and adoption of protective measures and operating procedures to confront this threat.

Advanced Laser-Protective Technologies[2]. From a technological point of view, several measures exist to counter these lasers threats:

- Broad-band absorption filters and dielectric single laser wavelength filters are available;
- Dielectric multilayer filters that block several laser wavelengths, or which are transparent only at several small

[2] See Annex 7.

wavelengths windows, are in the research and development/testing phase; these are being strongly protected by those nations which are developing them;

- Filters and other optical elements based on non-linear optical effects, i.e., intensity controlled absorption and/or reflection, are in the research stage; these are also being strongly protected by their developers;

- Specific designs of electro-optical detectors and detector arrays to provide a certain amount of laser hardening are also in the research and development phase, and strongly protected;

- Retro-reflective devices to threaten the enemy, in addition to safeguarding the friendly crew/sensors, are possible, but their use may result in an increased counter-detection susceptibility.

The factor limiting development of the above-mentioned protection measures may not be cost but rather the limitations imposed by basic physics. Solutions should be attainable against cheap, simple lasers. However, solutions to the protective filter problem against highly sophisticated laser systems may not be available, even in the year 2020.

Emerging laser technologies suggest that the laser threats of the future are likely to be high-power, agile, tuneable, and multi-line. If these protective technologies are not able to counter such threats, a different approach to protection will be required.

A closed cockpit (or threat-based closing of the cockpit), such as is described in Chapter 5, may be required. If adequate sensor hardening is available to prevent "blinding of the aircraft" that would lead to its crash; and if it does not intolerably reduce the ability of the crew to successfully perform its mission, the closed cockpit may prove the ultimate solution for crew protection.

Parallel studies of the problems associated with flying without a direct view of the outside world, and the optimal integration of the man with the sensor information, will minimise the risk and pave the way for technology in future aircraft. The ultimate response for protecting the human is the Unmanned Tactical Aircraft, as discussed in Chapter 8.

7.2 Future Combat Aircraft

Combat aircraft will remain central to aerospace power in the next 25 years. The manned combat aircraft will remain the primary platform for most air combat missions. The driving factor in choosing future fighter aircraft will, most probably, be cost. In considering the choice of new aircraft designs in this context, it is clear that for any given level of technological and organisational capability:

- The greater the commonality that exists between aircraft types, the lower the life-cycle cost of the fleet. The greater the diversity, the higher the cost;

- The greater the number of any one type of aircraft in service, the lower the life-cycle cost;

- In general, the higher the level of performance and the greater the diversity of performance attributes demanded of a new aircraft, the higher the life-cycle cost.

With these considerations in mind, it is clearly important to seek maximum commonality of use across NATO air forces, maximum commonality between the designs of aircraft in any one air force, and optimum balance between the performance attributes specified for new aircraft and the numbers of such aircraft that can be afforded within a given defence budget.

Upgrades. The development cycle of a combat aircraft, from setting the requirements until service entry, is 10 - 15 years; followed by an operational life of 20 - 40 years. This, plus economic constraints, means that, by 2020 a large portion of the fleets will consist of aircraft which are flying today, or at least, are on the production line or at the design stage. Economics will dictate that only a fraction of these aircraft can be replaced by new platforms. Therefore, these aircraft will need to be upgraded to provide even the minimum of essential combat capabilities.

The most likely upgrades will be:

- **Short-range air-to-air missiles** (AAMs) for air superiority, with high off-boresight capability and high agility, through thrust-vector control (TVC), leading to a larger no-escape envelope;

- **Beyond visual range** (BVR) **missiles** for air defence, with ranges of 100 Km+ and with ramjet propulsion for higher terminal manoeuvrability and, again, a larger no-escape envelope;
- **Air-to-surface missiles** (ASMs), using cruise missile technology for strike, with ranges of several hundreds of kilometres and precision guidance, possibly with man-in-the-loop for final target identification;
- **Improved defensive systems**, ECM and expendable and towed decoys to counter the advances in AAMs and SAMs;
- **Active self-defence** systems, such as short-range rockets or low-power lasers, to disable incoming missiles;
- **Improved sensors** to cue long-range weapons; e.g., longer range air intercept radar and infra-red search and track (IRST) systems for air-to-air missions; synthetic aperture radar (SAR) and mapping modes for air-to-ground missions;
- Improved high-capacity, jam resistant, **secure data links**, to share data with other platforms and to improve situational awareness.

Even if all of these possible improvements were made, there are limits to what an upgraded aircraft can do. Beyond those limits, only a new design can perform adequately. One such limit is stealth. Existing non-stealthy aircraft have large signatures; they will be increasingly difficult to conceal, as sensors advance to counter stealth. Ultimately, existing aircraft will be confined to stand-off strike missions and basic air defence in "safe" skies. The penetration of hostile air space, for air superiority or strike, will require a new generation of stealthy designs that also exploit advances in other technological areas.

A New Generation Fighter

Available and emerging technologies will make possible the cost-effective design of a New Generation Fighter (NGF) family, which performs the full range of operational roles. The NGF family could consist of three groups:

- The **single-seat, lightweight** group: air superiority, combat air patrol, and ground attack;
- The **two-seat, heavyweight** group: long-range interdiction, electronic support, and air defence suppression;
- The **special technologies** group: lift system and larger wing required respectively for STOVL from small through-deck cruisers, and CTOL from large conventional aircraft carriers.

The first and third groups correspond roughly to the US Joint Strike Fighter (JSF) programme. The second group may correspond to a tentative European Future Offensive Aircraft (FOA). In technical terms, the most difficult combination is the second group, which requires a second crew member, more fuel, and an aerodynamically more efficient wing.

The variants in the third group would be derived from either the first or second group. The lift system could replace the second crew member of the 'heavy' interdiction version, or replace internal fuel in 'light' ground attack versions. The three missions in the first group (also in the second), could be performed by the same aircraft, simply by changing conformal packs. This would create a partially "reconfigurable air force," with increased operational flexibility. Although some of this kind of flexibility already exists in 'multi-role' aircraft like the Grippen or the F-18, it would be taken further in the NGF family.

Weapons

The main armament would be missiles. These should be carried internally, e.g., with folding fins if small enough, or otherwise, semi-recessed. An AAM with an engagement envelope and agility at least equal to the Russian Archer is urgently needed to close that capability gap. A ramjet-powered BVR AAM with TVC would improve on the range and thermal agility of AMR AAM. Both types of AAM should be carried in sufficient quantity, e.g., 6 BVR and 4 short-range AAMs. A long-range munitions dispenser, like the UK's CASOM (Conventional Attack Stand-Off Missile) is too large for anything other than a semi-recessed carriage among conformal packs, if one wants to improve on a standard pylon mount. Glide bombs, short-range ASMs like Maverick, and even ARMs, could be carried in conformal packs, using folding fins and other space-saving measures for compact carriage.

A debatable point is whether an internal gun is worth the volume and weight penalty, plus the

engine compatibility tests, and the need to protect nearby avionics against vibration. Since the useful range of the air-to-air gun lies within the 'no-escape' envelope of modern AAMs with large OBA seekers and TVC propulsion, its use as a last-ditch dogfight weapon is increasingly less likely. In addition, modern anti-aircraft defences make gun strafing attacks on ground targets a high-risk/low-payoff mission.

The aircraft gun may still serve as a low-cost weapon against unsophisticated aerial targets, like helicopters or transport aircraft, and against soft, unprotected ground targets, like trucks and convoys. The value of such targets may not merit an ASM; the gun could be included in a conformal pack for such eventualities.

An important adjunct to the NGF would be miniaturised precision-guided munitions (PGMs), using high-accuracy terminal guidance and more effective warheads. The goal is to reduce the volume and weight compared with the current Mk 82 - 84 500 - 2000 lb bomb family, thus allowing internal carriage in larger numbers. Weapons miniaturisation is a critical technology for future combat aircraft, it is discussed further in the next section.

Critical Technologies for Future Combat Aircraft

For front-line combat aircraft there are particular technological characteristics that are of critical importance. Some of the more significant are:

- Stealth with Large Volume,
- Modular/Conformal Airframe,
- Weapon Miniaturisation,
- Pilot Associate,
- Defensive Measures,
- Advanced Propulsion.

Stealth with Large Volume. The Gulf War showed the advantage of stealth. In terms of strikes per sortie, the F-117, despite its unremarkable flight performance, was the most effective attack aircraft. Stealth alone enabled the crippling surprise attacks that demolished much of the air defence command and control infrastructure at the outset of the war. The surprise effect will be diminished in the future; the effectiveness of stealth will be pitted against improved sensors, like long wavelength and bi-static radars.

Yet, it may always be true that the stealthy aircraft has an advantage compared with the non-stealthy. It was once said of the battle tank that it was not invulnerable - but any weapon which can knock out a battle tank, can more easily destroy anything else that moves on the battlefield. Similarly, the stealthy aircraft is not invulnerable, but it is less vulnerable than a conventional aircraft.

Thus, the question is not whether stealth is worth having, but to what extent it should be pursued. Since stealth is a design feature that carries a lifetime penalty, it should be used to the minimum extent possible, after every other aid to survivability has been exhausted: mission planning, jamming, decoys, and stand-off weapons. Also, taking stealth to costly extremes, e.g., reduced accessibility, costly manufacture, and low volume, should be avoided. Suffice the example of two reconnaissance drones (Tiers 2+ and 3-) of the same cost: the stealthy one with one-third the payload and endurance of the non-stealthy one. The key issue is how to integrate stealth without compromising too much on other aspects of fighter design.

What is needed for the next fighter generation is a stealthy design combining aerodynamic and structural efficiency with large internal volume to carry fuel and weapons. Internal carriage must have high priority. External stores, like bombs, dispensers, pods, and fuel tanks, severely degrade stealth. As a bonus, internal stores will increase range by reducing drag.

Modular/Conformal Airframe. Having a single aircraft family to perform the full range of fighter missions will require a modular airframe, able to incorporate several options and variations, such as:

- A single or two-seat design,
- A single-seat STOVL version,
- Conformal fuel packs,
- A carrier-borne version,
- Variable-geometry outer-wing panels,
- Internal weapons carriage, augmented by conformal weapon packs,
- For ESM and SEAD, versions using conformal packs.

The basic airframe, together with all possible combinations of conformal packs (for fuel, weapons, electronics, decoys, jammers, et cetera), should be designed for stealth, combined with

aerodynamic and structural efficiency - a rewarding design challenge.

Weapon Miniaturisation. Accepting that internal weapons carriage is essential for stealth immediately leads to a high priority on weapons miniaturisation. The investment in miniaturising weapons may be more efficient than reducing weapons numbers, which requires more sorties for the same mission; and is more cost-effective than trying to increase airframe size, which raises cost. The weight of bombs in use today is the same as more than fifty years ago. Weight reduction should result from both advanced explosives and precision guidance. New munitions are being developed that can be as effective, with a smaller mass, as traditional explosives. Advances in sensors and guidance should be used to not only place the same amount of explosive close to the target, but to reduce the amount of explosive required. A balanced investment in weapons miniaturisation and high-volume, low-observable airframes could provide a stealthy weapons capability comparable to aircraft with external stores.

Pilot Associates. Fighter aircraft design has tended to use nearly the full potential of not only the available technology, but also of the pilot. In order for the mission to remain achievable, the pilot has evolved from a 'flyer' toward a 'manager'. Further evolution will demand that the role of pilot associates in the new fighter generation will have to be expanded, in order to keep the aircraft signature as small as possible, by removing the requirement for an additional crew space, while preventing the pilot from becoming overloaded with tasks. Typical functions might include:

- To engage targets by order of priority, according to the threat they represent;
- To enhance survivability by reducing pilot workload and by alerting the pilot to impending threats;
- To recommend the best defensive or evasive action relative to a new threat.

The increased use of pilot associates will serve to keep the amount of information that is presented to the pilot, and which he/she is expected to assimilate, within acceptable bounds. Data from several sensors (radar, radio, infra-red, electro-optical), and several platforms (own aircraft, satellites, other aircraft through data links) should be displayed in a correlated form. Multifunction displays will cover a greater area (a 'blind-glass' cockpit is the limit), and offer increased versatility as to what data (flight data, weapon status, navigation, threats, friendly forces, et cetera) is presented - and how it is presented. Means of command will include throttle and stick, voice commands, push buttons, and touch screens. These will mostly input the decisions of the pilot as manager, but will not be used to perform routine operations.

Defensive Measures. Given the high threat level, both in air combat and ground attack, the new generation fighter will need five 'layers' of defence:

- Careful **mission planning** - to minimise exposure time;
- **Stealth** - to reduce the probability of detection during that time;
- **Decoys** - to divert attacking weapons if detection was not avoided;
- **Manoeuvrability** - to take evasive action if an approaching weapon cannot be diverted;
- **Self-defence systems** - to destroy approaching weapons if no diversion or evasion is possible or desirable.

It is becoming increasingly clear that the first four layers of defence are not enough. The 'no-escape' envelope of AAMs - where no evasive manoeuvre is effective - is expanding. Missiles with dual-frequency IR seekers (operating in the 2 and 10 micron bands), dual mode (IR and radar) seekers, or imaging seekers, are increasingly difficult to deceive by chaff and flares. Decoys must become more sophisticated, and be able to follow violent aircraft manoeuvres.

As some of the first four layers lose effectiveness, more emphasis must be put on such active self-defence methods as:

- Laser directed-energy weapon systems[3]. Because they will operate at short range, these systems will not require high power;
- A rocket system with a proximity-fused warhead.

Active self-defence will only be fully effective in combination with the other defensive measures. It

[3] See Chapter 7.

will not, by itself, be sufficient to protect all targets.

Advanced Propulsion. Advances in propulsion technology [4] have been among the main contributors to the rapid pace of evolution of fighter generations. The thrust of jet engines has been steadily increasing, whereas size and weight have increased much less, and sometimes have even been reduced. Besides a large improvement in thrust-to-weight and thrust-to-volume ratio, there has also been a reduction in specific fuel consumption, so that total fuel consumption has increased less than thrust. An important qualitative change is that the dry (i.e., un-reheated) thrust of a single engine is now sufficient for supersonic cruise - without the factor of 2 - 3 penalty of afterburning on specific fuel consumption.

Thus, a single engine that enables supersonic cruise and provides high performance at a gross weight sufficient for useful payload and/or range is conceivable. It would be of the "usual" size (less than 1m diameter, 4m long) and weight (less than 2 tonnes), and have "normal" total fuel consumption. This engine, in a stealthy airframe with large volume and conformal fuel/weapon packs, will enable the design of the NGF family.

Summary

The major challenge for designing, acquiring, and maintaining a combat aircraft fleet in the coming years will probably not be limitations of technology, but finding the proper compromises between military requirements, national priorities, industrial interests, and economic issues. To maximise effectiveness and survivability, the investment in aircraft and weapons (missiles, guns, bombs, et cetera) must also be balanced. For all of these compromises, the most important criteria will be cost.

7.3 Future Heavy Transport

The development of a large, high-subsonic speed airlifter with greater than 10,000 NM range and a payload, weight, and volume capability at least equivalent to, if not greater than, the current C-5 aircraft, is possible. At the large aircraft systems level, advances in aerodynamics, propulsion[5], structures and subsystems are required to reach the capabilities mentioned above. In aerodynamics, continued research in drag reduction (i.e., laminar flow, boundary layer control, compliant/smart skins) and high aspect-ratio wing design is required in order to facilitate the long range capability.

There is also the potential for radical configurations that use the advances in aerodynamics, stealth, materials, and structures technology to provide lightweight span load carrying structures. The development of interdisciplinary design approaches using computational fluid dynamics, structures, materials, and electro-magnetic computer codes is the key to these new designs.

Such an aircraft would initially be designed for airlift, but could also be designed, or adapted for, non-logistics roles.

Airlift

Such an aircraft used as airlifter would radically change the deployment, sustainment, and reconstitution of forces. It could deploy, fully loaded, from any main NATO operating base in Europe or North America to any area of operations within NATO's sphere of interest. It would not require air refuelling, or refuelling at any intermediate operating location, before delivering its cargo and returning to a NATO main operating base. For missions of average length, the aircraft could be repeatedly turned and loaded without refuelling, thereby significantly increasing the sortie rate.

Tactical Assault Transport. NATO's role in carrying out humanitarian missions in possible or actual hostile areas, coupled with the desire to minimise risk to personnel in these and other operations, will drive the requirement for the use of stealth technologies on transport aircraft. With the proliferation of shoulder-fired, anti-aircraft missiles, a balanced approach to stealth will be required. This will have a major impact on vehicle design, as the level of stealth achievable in any vehicle is dictated mostly by its external shape. Future assault transports may require radar cross-sections of less than 0.1 meters, and a significant reduction in infra-red signature. These requirements may only be met by the development of very unusual designs, such as span-loaded aircraft (i.e., flying wings).

With some significant research in high-lift devices and fluidic control, a C-130 size assault

[4] See Annex 8.

[5] See also Annex 8.

transport with stealth features (radar cross-section less than 0.1 meters), double the range, and the ability to operate from unprepared landing sites of 500 meters or less with a California Bearing Ratio of 5 (approximately the firmness of a dry soccer field), is possible. This aircraft could be useful in many special roles: counter-terrorism, hostage rescue, embassy support, and support of special operations forces. The aircraft would have all-weather, night-operation capability, with the ability to locate and land any place in the world without the use of external landing aids. En-route mission planning and intelligence update would be possible. Using advanced cockpit/helmet-mounted displays and three-dimensional digital mapping techniques, totally autonomous operation will be possible with night, low-level infiltration/extraction being the norm. With partial fuel load, take-off distances of less than 300 meters would be possible. This type of aircraft could find a ready market for use in commercial transport operations. In fact, the numbers of aircraft required for commercial operations could be larger than any military buy. An attractive approach for procurement of this class of transport would be to build the commercial version, adding the uniquely military equipment as the aircraft progresses down a common assembly line. Spares replacement and maintenance could be contracted to commercial airline companies with some military capability, as required, being maintained for combat operations. This could result in an affordable replacement for the C-130 aircraft.

Precision Air Drop. A significant increase in resupply via precision air drop is envisioned. With this capability, the necessity for actual landings is reduced. It is well within reason to postulate that precision air drops within 3 metres of the intended impact point will be possible with the use of GNSS, advanced parachutes, and new air data systems. This capability, coupled with automated logistics supply systems, would make military overnight delivery possible anywhere in the world.

Precision air drop will require advances in the ability to measure wind shears, real time, in the drop zone, and the development of a simple, throw away control system that includes the parachute. To ensure that cargo landed in the desired area, cockpit displays would have to be developed in order to use the real-time wind shear data to designate an aim box for cargo release. This would provide on-demand resupply of personnel and materials, and facilitate the sustainment of isolated areas.

Air Refuelling. Air refuelling capability will continue to be a major influence on the deployment of forces to advance operating bases. The ability to refuel a flight of aircraft at one time, and then stay on station to refuel several more flights of aircraft, would be a significant force multiplier. This would require a large airlifter with advances in multi-point refuelling. With optimised station-keeping, multi-point refuelling capability, additional fuel as cargo, and by trading range for off-load capability, this aircraft could have the potential of replacing between 5 and 8 of the KC-135 aircraft now required to provide the same fuel off-load.

The greatest impact on air refuelling will be in the boom operator station, and in the location and design of the refuelling probe/drogue chute. The use of virtual reality in the design of the boom operator's station, and the potential use of stereoscopic technology will significantly reduce the boom operator's work load. The use of multi-body computational fluid dynamics in the determination of vorticial flow, and the use of modern controls, will significantly reduce the work load associated with the refuelling task, and allow more refuellings per aircraft.

Greater Autonomy and Lower Maintenance. The next generation airlifter will have the ability to locate and land at night and in weather, on any air base in the world, using only on-board generated landing guidance. Advances in cockpit/helmet displays, digital terrain mapping, global positioning systems, and data storage will give the pilot the ability to electronically "see" the runway in a real-world scenario equivalent to visual flight rules. With some ground support for relaying information on ground threats, the system could be updated in flight to provide an approach that avoids known threats. Neither the arrival base nor the aircraft would have to emit any signals. Operations would be accomplished in total blackout conditions, thereby significantly reducing the threat to the base and aircraft.

With significant increases in both reliability and maintainability, no aircraft support personnel would be required at the forward base. The aircraft would have its own on-board self diagnostics for monitoring the maintenance state of the aircraft. The reliability of the subsystems would be such that scheduled maintenance would be performed once a year. Incorporation of

integrated subsystems, including more electric actuators, advanced cooling techniques, and integrated starter/generators, would obviate the requirement for hydraulic and starter carts. New redundant management techniques would allow fault isolation at the lowest level, without mission or safety degradation, and eliminate the false systems' warnings that impact today's sortie generation capability.

Continued research in propulsion will result in better fuel mileage, increased thrust-to-weight, environmental compatibility, and increased engine reliability. Advances in the subsystems area will provide some of the most dramatic changes. Integrated sensors, avionics, and subsystems are the key to increased reliability, and to performance at reduced costs. Tĕchnical advances in high-power electric actuators and brakes will reduce, or eliminate, hydraulic systems on aircraft. Integrated power generation and environmental units will provide increased power and cooling capacity, thereby increasing avionics component life. Integrated sensor suites and avionics will lead to common modules that will be programmed for specific functions. These functions could be altered to accommodate, or take over, the functions of faulty units. This will result in gradual/controllable degradation in mission capability, rather than mission failure.

The biggest impact on the utility of extremely long-range airlifters is the effect on total life-cycle costs. With the reliability and maintainability objectives achievable by 2020, the requirement for prepositioning spares and support personnel will be minimised, if not eliminated. More importantly, the requirement for maintenance personnel at the home station is substantially reduced. The use of advanced diagnostics and artificial intelligence maintenance aids will make two-level, if not one-level, maintenance a reality. All of this technology can be used to significantly increase the reliability of the system, while retaining comparable performance. It is possible to postulate a system that has the redundancy and reliability to have a scheduled maintenance cycle of 250,000 NM, or one year, with no need for accomplishing unscheduled maintenance.

Non-Logistics Roles

Large transport aircraft have traditionally been modified for a variety of other missions and roles: AWACs and JSTARs, for example. This trend will continue, and there will be opportunities to develop some systems "from the ground up" for special, non-logistic roles. Three examples are described: Information Acquisition, a Directed-Energy Weapons Platform, and an Airborne Vehicle Carrier.

Information Acquisition. The natural extension of current roles for a large transport aircraft would be in reconnaissance and/or surveillance. The future large airlifter would have the volume, power, and endurance to perform this mission for extended periods of time. It could serve as a follow-on for AWACS, as a future platform for ELINT operations, and/or as a future carrier of long-range reconnaissance sensor systems. With advances in data fusion, it could also provide processed information directly to the units needing the information.

Directed-Energy Weapons Platform. As a follow-on to the Airborne Laser (ABL) concept, a large airlifter would have the volume and power necessary to accommodate the next generation deployment of laser and microwave weapons.

Airborne Vehicle Carrier. The large airlifter could also be used as an aircraft/missile carrier. It could function like an AWACS, but have its own offensive capability. This would provide the capability to reach out and touch someone anywhere in the world - without having to risk the lives of NATO air crew. In a simple system, targeting information/designation for ground attack would be provided from another platform, such as an F-117. The airlifter would be the munitions carrier, and the F-117 would be the target designator. This would give the F-117 the ability to attack, assess, and re-attack several targets on one sortie. More advanced versions would use remotely piloted vehicles and/or micro-fighters, which are launched and recovered from the large airlifter. The remotely piloted vehicles would be controlled entirely by the personnel in the large aircraft. It would function as the "Mother Ship" and orbit close to the area of interest, but not be at risk. With sufficient range of the UAVs, the Mother Ship could remain in international airspace, thereby providing quick access to an area without the need for overfly permission. To quickly provide a physical presence, or to demonstrate intent, it could be launched and recovered from main operating bases in NATO. No forward basing of expendables or personnel would be required.

This same Mother Ship concept could be used to perform the air-to-air role, particularly in no-fly zones and low-intensity areas. This could be a very cost-effective solution when the probability of requiring an intercept is low, but Alliance policy or treaty has dictated a need to provide protected airspace. It could also be used in the initial build-up stage of a conflict to provide air cover for expeditionary forces, and to provide the air picture in areas where adequate operating bases and command and control facilities are not available.

Dual Use

It is conceivable that this class of transport aircraft would fulfil a need in the civilian market. Although the passenger market immediately comes to mind, it will probably be the cargo market that would use this capability first. With continued growth of the world economy, particularly in Asia, and the wide implementation of the "just-in-time" delivery philosophy, a requirement for a large commercial cargo airlifter with most of the design characteristics of the military aircraft can be confidently predicted. Such an aircraft could provide an economical solution to the parts supply requirement, and support the continued growth in the overnight delivery market. Widespread commercial use would provide a potential surge capacity to meet the needs of major military missions.

7.4 Future UAVs

The Unmanned Aerial Vehicle (UAV) will continue to evolve (see Figure 7-1). It will become increasingly valuable in a variety of roles, particularly RSTA, communications, and electronic warfare, due to developments in two areas: long-range/long-endurance technologies and miniaturisation.

Long Range/Long Endurance

Unmanned vehicles with range/endurance greater than 5000 NM/100 hours will become available. Such vehicles, will have the ability to stay on station 24 hours a day for days/months. They will be capable of performing missions in ways that obviate today's requirements for the deployment of special launch and recovery equipment, support personnel, and logistics to forward areas. Operations from main operating bases in NATO would be the norm, with the ability to react instantaneously - without having personnel exposed to hostile actions.

These vehicles will also have different levels of stealth, to allow for covert operations and

Figure 7-1: Advanced Concept UAV - Artist Representation

surveillance. It is well within reason to expect that these vehicles could carry weapons, could designate the target for weapons, or could, itself, be the weapon. These vehicles could be complementary to the long-range airlifter in its role as "Mother Ship". They could receive their in-theatre assignments from the Mother Ship and provide the Mother Ship escort protection, and/or broader area coverage, without increasing the required manpower.

The ability to stay aloft for days at a time and to "stare" at a designated area of interest, in combination with future sensors technologies, will make these vehicles excellent RSTA platforms. In addition, they will be able to operate line-of-sight for most missions, thus taking advantage of optical data links for greater bandwidth communications.

This ability will also be useful for information management missions in which the UAV could become a node in a distributed command and control architecture, either as a simple relay or as a data fusion point in support of multiple sensors.

UAVs can have both ECM and ESM roles. The closer a UAV can approach its target, the greater the increase of the flux density at the target. Therefore, greater disruption can be achieved without increasing power output. If an ESM receiver is slaved to the jammer on this same platform, the jammer can adapt its output to respond to the modes which are provoked by the ECM. The improvements in sensor technology will increase the bandwidth over which the sensors are responsive, and also reduce the time to retune the jammer. These measures will improve efficiency and allow the operator to programme the device to multiplex over a larger number of targets. Even with increased complexity in the modulation applied, the ability to add false targets into primary radar and/or to overload a secondary radar becomes feasible.

In an ESM role, the UAVs can provide platforms for carrying electronic sensors close to, and into, enemy territory. The means of transmission and recovery of acquired data will be broadly similar to those used for RSTA sensors.

Micro Vehicles

There is the potential for the development of small unmanned vehicles with almost unlimited endurance. These vehicles would be the size of a large bird, and have a small but effective payload. A flock of these vehicles, with different payloads, could provide continuous coverage over a given area, with the objective of providing data that can be fused at a base location. The small size of these vehicles, advances in passive sensors, and low probability of intercept communications would give designers of these vehicles the latitude to achieve a very low-observable signature. These vehicles could be built to resemble birds from a distance, thereby adding to their stealth characteristics. They would be hard to detect and expensive to intercept - a SAM or AAM would cost more. They could also swamp defences by presenting too many targets.

This class of vehicle will satisfy the same basic design requirements as other unmanned vehicles, but will exploit advances in miniaturisation and new technologies that are now in research. Foremost is the development of all-electric propulsion that uses advanced battery and solar cell technology to power the vehicle. Power-by-light technology and all-electric actuation are technologies that may also have an important part to play.

With advanced materials and virtual manufacturing techniques, these vehicles would be very affordable. It would be possible for several vehicles with different payloads to be used to cover the same area, providing not only redundant coverage, but also economical mixed-sensor packages. The level of balanced signature control would also vary, depending on mission requirements. Design trades in these technology areas, including maximum speed, will give commanders a matrix of capable vehicles that are affordable solutions for a variety of missions.

Dual Use

The cost of developing these unmanned systems could be offset by contributions from their non-military applications. Indeed, there will probably be more use of these vehicles for non-military purposes than for military missions. Environmental studies, communication link, and surveillance support for natural disasters, border patrol, drug interdiction, and agricultural surveys could use the same basic airframe. What would change would be the payload. This versatility could be a source of danger, as these vehicles could be easily obtained and employed against the Alliance and its members.

7.5 Summary

The evolution of these systems follows the trend lines set out in Chapter 2. They will lead us into a future scenario dominated by high-lethality systems, at speeds up to, and including, the speed of light. They will provide greater opportunity to affect the battlefield without exposing the human operator, and to provide flexible, sustainable capabilities to future warfighters.

Perhaps, however, the most promising capabilities will arise from the convergence of these evolving technologies. For example, as discussed above, future heavy-lift concepts in combination with miniature UAVs could provide unparalleled capabilities. Any successful convergence of high-power lasers and future air vehicles would have profound implications for NATO, and would change the very nature of aerospace combat.

Such innovative combinations can also give birth to radically new concepts, such as the Unmanned Tactical Aircraft, which represents the convergence of fighter and UAV technologies, supported by information and sensor technologies. This pattern of converging evolution, in combination with new technology, will doubtlessly provide unforeseen opportunities for innovative solutions, as well as the basis for revolutionary advances in aerospace systems.

8. NEW SYSTEMS CONCEPTS

Over the next quarter century, certain "new" systems concepts will arise. Although they may be based on research that has been on-going for decades - space flight, hypersonics, et cetera - when realised, these concepts have the potential to radically change the nature of conflict. This study focuses on three such concepts:

- Unmanned Tactical Aircraft: capable of wholly or partly autonomous performance of tactical air missions;
- Hypersonic Air-Breathing Missile: a Mach 8 air vehicle using a storable, kerosene-based fuel;
- Access To Space: a next generation of lower cost, reusable, space vehicles.

8.1 Unmanned Tactical Aircraft

The Unmanned Tactical Aircraft (UTA) is a concept to integrate technologies into a complete tactical airpower system, producing a general purpose, high-performance combat aircraft capable of performing a full range of combat missions without the physical presence of a pilot in the aircraft. The concept encompasses a broad class of recoverable vehicles designed to conduct tactical missions, using on-board weapons and sensors. UTAs will exploit the many sources of off-board information available in the future theatres of operation. Flexible off-board control of the air vehicle places the operator at the centre of the emerging information architecture, whether the control station is ground, air or sea-based. This will allow the operator to exploit information from on-board systems, off-board reconnaissance and surveillance sensors, and theatre data bases of information from all sources.

System Overview

UTAs will capture the benefits of both manned and unmanned operations. As an unmanned aircraft, it can be utterly fearless, performing missions which are considered too hazardous for personnel; and it can be expended, if required by the situation and the value of the tactical objectives involved. Additionally, it can tolerate sustained manoeuvres about all axes, extremely long-duration operations, and hazardous environments, without regard for the physiological limitations of the human.

The man in the control loop will supply the rational, judgmental, and moral qualities of the human operator, and provide the flexible operational capabilities needed to operate in a wide variety of situations.

The UTA concept is the only one which allows these benefits to be captured in a single system. It is envisioned to support a range of missions of increasing complexity: from reconnaissance, at the low end of complexity; to air-to-air combat, at the high end. At the highest levels of complexity and capability, the intervention of a human operator is essential. In this case, the key to the UTA concept is to "Keep the Operator's Head in the Cockpit while Leaving the Rest of Him at Home". Thus the UTA will be uninhabited, but will otherwise function as a piloted vehicle, enabling the operator to use the full range of human judgement, intellectual capabilities, and moral authority. This is the key that will allow UTAs to operate as flexibly and effectively as manned aircraft. UTAs will be able to operate from ordinary airfields, and to fly in controlled airspace. They will conduct missions in peacetime situations, in crisis situations, and in wartime. UTA operators will be able to observe rules of engagement, to make the critical decision to use, or refrain from using, force, and to operate in uncertain and confusing situations.

For less complex missions, fully autonomous aircraft are already a reality. For the more complex missions, the objective is to automate all but the highest level decision-making processes, those which require human judgement. The technology areas of sensors, information processing, decision aids, and real-time mission planning, coupled with advanced automation technologies, will make the concept of the UTA a reality by 2020.

With the current choices in air vehicle systems, there are limited degrees of freedom in fielding and operating tactical air forces, under budgetary and mission constraints. UTAs offer a system alternative that has fundamentally different characteristics - a new degree of freedom for force planners. UTAs can have dominant performance in some missions, and might be quite

limited in others. Perhaps most importantly, it can offer a reduced cost option to supplement, or complement, piloted aircraft. These characteristics suggest that UTAs can enter the force mix of many national air forces if the development of the technology bears out the promise of the concept.

The emergence of the UTA as a viable concept rests upon the confluence of technology trends in the hitherto separate areas of unmanned and manned air vehicles, supported by the explosion in information and communications technologies.

Only recently have UAVs begun to receive increased emphasis. Examples include the Israeli operations against Syria, the use of the several short-range systems during Desert Storm, and Predator operations in Bosnia. The latest generation of US UAVs - the Tier II+ and Tier III Dark Star HAE (High-Altitude Endurance) systems - will fully embody the advances proven in these systems, and advance far beyond them in system capabilities.

Although these UAVs are advanced aerodynamic vehicles with highly capable sensor systems, the major advances in their capabilities will be in the area of command and control, including near real-time control by manned operators. HAE operators will be given intimate knowledge of the vehicle and all its systems, and they will be able to completely control all mission parameters in real time. They will be supported by advanced situation displays, and mission planning tools capable of adapting complete missions to changing tasks and tactical situations in time scales of minutes.

Advanced concepts for integrating strike and ISR (Intelligence, Surveillance and Reconnaissance) operations envision synchronising manned strike aircraft and HAE missions by integrating these man-in-the-loop remote control capabilities with strike command and control, in real time.

UTA designs will also have an advantage in signature reduction. Manned aircraft require a cockpit located high and forward on the fuselage. This largely dictates the layout of the remainder of the aircraft. UTAs can be laid out specifically to address difficult signature problems, such as inlets and exhausts, wing-body intersections, and antenna and optical aperture locations. Innovative layouts can be used; for example, locating more observable systems like landing gear doors, access doors, and drains on the "top," and designing the "bottom" to be fair. There is no up or down orientation to a vehicle without a pilot. Different materials can be used for signatures design, since UTAs will fly different mission profiles and have a shorter design lifetime than manned aircraft.

Mission Concept

The operating concept for UTAs suggests that it is intended to be capable of the full range of piloted aircraft missions. This is a goal which seems to be largely attainable, based on the rapid growth of the technologies which support UTA. However, it is unreasonable to believe that all missions can be done equally well, or even done at all, in the same generation of vehicles. UTA capability will grow as the technology develops, and as user communities learn how best to use systems of this kind.

The class of UTA vehicles extends from more flexible and capable versions of currently deployed surveillance UAVs to future full-spectrum unmanned aircraft. Missions for UTAs, in order of increasing complexity, are as follows:

- Intelligence, Surveillance and Reconnaissance and Battle Damage Assessment (BDA),
- Electronic Warfare (EW),
- Suppression of Enemy Air Defence (SEAD),
- Fixed-Target Strike,
- Theatre Ballistic Missile and Cruise Missile Defence,
- Air Defence,
- Interdiction and Mobile Target Strike,
- Close Air Support,
- Air-to-Air Combat.

This list encompasses the core tactical aircraft mission set. Other missions, such as unmanned airlift and special mission aircraft, will also be possible.

RSTA and EW support missions are likely to be feasible in the near term. Unmanned RSTA is currently being done with UAVs. EW could be done with these airframes or with modified conventional tactical aircraft. For these missions, the UTA concept would apply to improving the currently limited operator interfaces to expand the mission envelope, and to allow these missions to be performed more dynamically, and in a greater variety of operating environments.

SEAD and fixed-target strike missions are also possible in the near term, although the full potential will not be reached until the technology is fully mature. These missions are a short step for UTA, since the technologies needed to employ these sensor and weapon systems are essentially available today. The major technology challenge will be to develop and demonstrate the methods to operate an unmanned aircraft like a piloted aircraft, using air traffic control procedures, operating from ordinary airfields, and so on. These are likely to be the first combat missions for which new UTAs are acquired.

The mobile target and the close air support missions will be more difficult, since the UTA must search for and find its target, based on cross cues from other theatre assets, or on information from its own sensors. In either case, the on-board system must eventually acquire the target and transmit data back to the operator, so that he/she can choose aim points and responsibly give consent for weapons release. All of this must be done in a very short time, which will stress communications and data processing systems. Human factors in the operator interface will be important to reliable performance by the remote pilot. Extrapolating sensor, information processing, and communications technology, this does not appear to be an insuperable obstacle in the medium term (10 - 15 years).

Air-to-Air Combat will probably be the most difficult mission for UTAs, because it is so dynamic, and it depends so heavily on pilot skill and situation awareness. BVR (Beyond Visual Range) combat would seem to be quite compatible with the UTA concept, but it cannot always be assured. The applicability of UTA technology to close-in combat is in question. Much of what is done in this situation is based on the pilot and his/her ability to monitor sensors and visually acquire the attacking aircraft. The UTA must remotely emulate the pilot's visual cues based on imaging and other situation awareness sensors on the aircraft that downlink the data in real time to the control station. This requires a tremendous amount of bandwidth, and must be done in real time. There will be communications problems because of close proximity of several aircraft and highly dynamic manoeuvring.

Balanced against this is the possibility that the UTA will have a large manoeuvring advantage over a manned adversary aircraft, and may be a match for enemy missiles in some situations. This will simplify the mission, but not quite relieve the need for the highest level of information exchange, and the most severe demands on the situation awareness of the remote pilot. This mission will probably be the farthest term application for UTA; ultimately, its feasibility has yet to be established by our understanding of the technologies involved.

Expanded Options

The advantages of unmanned operations in high-risk environments are apparent. UTA can perform tactical air missions without exposing air crews to risk of capture or loss. This is a particularly valuable attribute for operations other than war; politically sensitive operations where the capture of Alliance personnel may have wholly disproportionate negative political consequences; and operations with high value, but not of a high enough value to justify the probable loss of Alliance air crew lives.

In some cases, hazardous missions can be performed by cruise missiles, and this will continue to be a good solution for the foreseeable future. However, many missions of this kind must be undertaken under conditions of uncertainty, poor planning data, and complex (perhaps politically sensitive) rules of engagement. Currently, these factors almost always make manned strike the preferred option. UTAs will be capable of combining the advantages of manned and unmanned operation, so they will offer a fundamentally new way to approach this class of missions.

Finally, capitalising on the explosive growth of theatre information systems for real-time intelligence, surveillance, and reconnaissance (ISR), situation awareness, and targeting, the UTA concept can enable missions to be performed in entirely new ways. Fusing information from many sources will allow UTA pilots to compensate for the reduced situation awareness inherent in remote operations. It will allow this information to be used without the need to send large amounts of digital image data to cockpits of manned aircraft. This is an important element in making the UTA feasible and effective.

Concept of Operations

One view of the concept of operations for UTAs is presented in Figure 8-1 (following page).

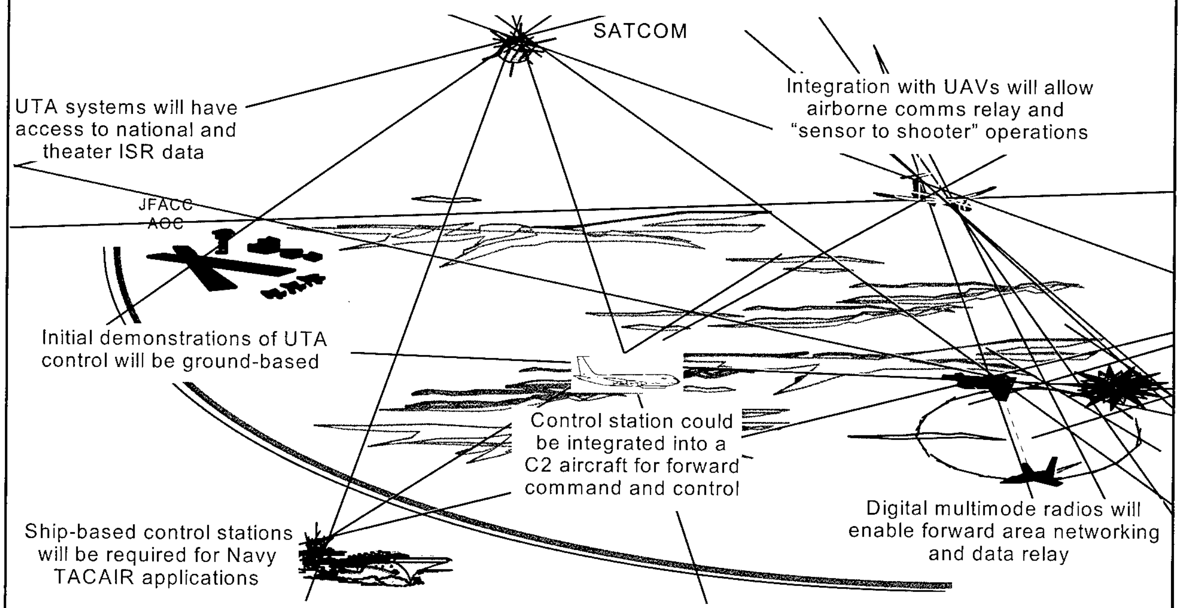

Figure 8-1: UTA Concept of Operations

UTAs could be land-based or sea-based; they could be conventional take-off and landing aircraft, have a vertical take-off and/or landing mode, or could be launched and recovered by a large "mother ship" aircraft. The choice will be based on the ultimate roles and missions for the air vehicles when they are designed. Command and control of the UTA force will be accomplished using line-of-sight and satellite communications data links. Airborne relay can be used to extend the range of line-of-sight links as for any other aircraft communications system. Capabilities in communications sets will allow airborne networks to be formed among tactical aircraft - UTAs and piloted aircraft - in the local area of operations. This will facilitate data sharing, and may also be a feature in extending the effective range of line-of-sight data links, particularly in areas with difficult terrain masking.

The pilot's control station could be land-based, ship-based, or integrated into an airborne command and control aircraft. In the longer term, it may also be possible to integrate it into the cockpit of other tactical aircraft. The airborne control option offers the maximum flexibility, but will pose the greatest miniaturisation and integration challenges. The initial demonstrations of the control station will most likely be done using a ground station that can make maximum use of commercial equipment prototype hardware and software during the development phase. The shipboard control option is midway between ground and air basing, in terms of system integration and equipment miniaturisation, but offers significant system integration challenges of its own, particularly in the area of communications.

The key to the UTAs flexible capabilities will be the achievement of **variable autonomy** in the system as a whole. Variable autonomy refers to management of system functionality to allow the pilot to control any or all system functions, depending on the tactical situation and operator's judgement, while making maximum use of system autonomy to control all other functions.

The UTA will be capable of complete autonomy for all functions except authorisation of the use of lethal force (weapons release), and will normally operate in a nearly autonomous way. The pilot, assisted by systems within the control station, will be capable of direct control of nearly all on-board functions, but will normally control only a few functions directly, and will serve as a mission objectives controller. The system (on-board and off-board systems) will be capable of adapting to changes in the pilot's preferences for control and in the situation (for example, failure modes and communications outages) to vary the degree of autonomy to best suit circumstances. In this way, the creativity, skill, and moral judgement of the pilot and the autonomous capabilities of the

computer-controlled system can be **complementary**, rather than substitutes for each other. This is the core enabling technology area for UTA; achieving it will be the fundamental challenge in realising the full promise of the system.

Total System Concept

A schematic of the basic concept for an integrated UTA system is shown in Figure 8-2.

The operator interfaces with the flight system using a pilot mission interface. This integrates on-board information (avionics data and on-board sensor data) with off-board information (planning data, support data, and intelligence, surveillance, and reconnaissance data) to enable mission functions to be performed. This view of the system clearly shows the core issues that must be addressed to make an integrated UTA system a reality, including:

- On-board sensor control, data management and multi-sensor system integration,
- Avionics systems,
- Secure data links from aircraft to operator interface,
- Pilot mission interface integration,
- Displays and human factors,
- Off-board data integration,
- Information processing and fusion,
- Mission planning and control.

Affordability Considerations

The principal technical impetus for UTA is provided by the performance and the unique mission opportunities it has the potential to create. However, its impact on affordability is equally distinctive, and will be, in the perceptions of some, the more important factor.

For a given range/payload performance, a UTA can be smaller and lighter than an equivalent manned aircraft. Eliminating crew systems may be worth 10 - 15% in weight. This may be worth an additional 5 - 10% weight savings when a new design is closed around it. New systems, materials, and structural techniques for an airframe with reduced lifetime flight hours may be worth an additional 10 - 15%. All-in-all, a UTA could be 30 - 40% smaller than a piloted aircraft. Since aircraft with equivalent avionics and weapon systems are bought "by the pound," this will result in a substantial decrease in acquisition cost. In addition to designing for enhanced performance or reduced signatures, reduced cost can be factored into the requirements and design process, allowing a more flexible

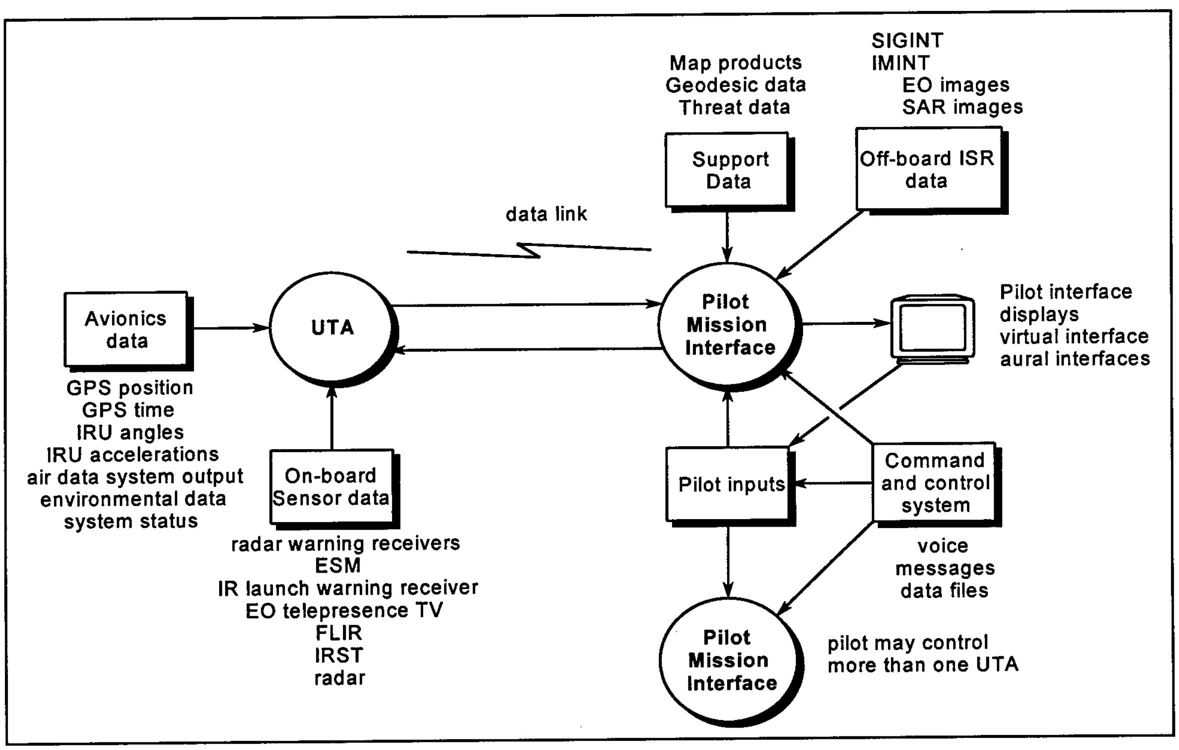

Figure 8-2: Schematic of Conceptual UTA System

approach to designing affordability into the system.

UTA systems are envisioned as operating much like a piloted aircraft during wartime, but they will operate very differently at other times. A piloted aircraft must be operated regularly in peacetime in order to maintain air crew proficiency, exercise avionics and weapon systems, and keep the aircraft in flying condition. A 15-year lifetime with 30 hours of training per month results in a 5400 flight hour lifetime; adding wartime hours yields design lifetimes in the 7000 hour range. This has a fundamental impact on the way the piloted aircraft is designed and maintained, and therefore, on how it accrues cost.

UTAs will fly very infrequently in peacetime. Its characteristics will be more like a "wooden round" weapon or a cruise missile, than a tactical aircraft. Since the pilot operates the UTA through a remote interface, it does not really matter whether or not the aircraft is actually flying for the pilot to receive tactical training. Flight skills, such as take-offs and landings, refuelling, formation flying, and tactical manoeuvring are not significant, since they will mainly be accomplished autonomously by on-board systems, guided by pilot input on mission objectives. All of this training can be accomplished using interactive simulations of the battlefield and the real pilot interface equipment - training as the operator will fight. This will reduce lifetime flight hours by a factor of 3 - 5, fundamentally affecting UTA design requirements and cost relationships.

UTAs as a "wooden round" system will operate and be supported differently than manned aircraft. Only a few UTAs will be fully operational at a given time. This will require only a cadre of maintainers and supporters to be active and incurring cost. The active units will rotate through the stored force over time, evening out the flight hours and keeping the force as a whole in readiness. This breaks the direct connection between realistic pilot training (which is required) and actual flight operations (which incur substantial recurring cost). Separating training from flight operations will allow O&S (Operations and Support) costs for the airframe to be reduced dramatically - perhaps up to 90%. Overall O&S cost may be reduced up to 50%, depending on manpower policies and mix of aircraft (manned and unmanned) in organisational elements - wings, carrier air groups, et cetera.

For many of the missions envisioned for UTAs, particularly high-complexity missions such as air defence or interdiction, an operational concept would incorporate the combined and interactive use of both UTAs and manned aircraft. In these cases, training would require the actual flight of the UTA, not for the training of the UTA operator, but for training the crew of the manned vehicle in controlling the UTA; and to address issues such as deconfliction. Nonetheless, the training flight times for UTAs should still be considerably less than those of manned aircraft, and should decrease further with the development of advanced simulators.

At our current state of knowledge, arguments for affordable UTAs are compelling, but still heuristic. Detailed cost and operational effectiveness assessments will provide definitive affordability estimates.

Technology Requirements

It is important to note that a variety of technologies must be developed in parallel in order for the UTA to be a successfully integrated system. These technology developments include: control station and human operator interfaces, secure communications, full-spectrum sensors with significant data processing and fusion, aircraft design, automated control, and high-bandwidth technology and autonomous mission management[1].

Hostile Exploitation

Hostile exploitation of hardware is a significant risk for UTAs, as it is for manned aircraft. It must be assumed that hostile forces will develop and deploy unmanned tactical aircraft in the future. In addition to their utility for conventional military forces, as described above, they could have special utility as delivery systems for terrorist weapons against civilian targets, and for weapons of mass destruction against all military and civilian targets. These kinds of capabilities could be of interest to a variety of hostile forces, including national military, extra-national, and terrorist organisations with the means to deploy advanced weapon systems. The UTA could become an effective, or even preferred, weapon for delivering special weapons because of the stress it could inherently place on cruise missile

[1] Relevant technologies are addressed in Annex 5.

defences, conventional air defences, and national airspace management systems.

These are serious exploitation problems; moreover, simpler systems could suffice. Even if high-level proliferation occurred, it is unlikely that the advanced UTA technology as described in this chapter would be crucial to the development of such simpler systems. UTA technology is intended to allow flexibility, precision, and human moral control in unmanned lethal weapon employment. These high-cost attributes are not as important to those who wish to use unmanned systems for employing weapons of mass destruction or as terrorist weapons. The technologies for vehicle autonomy and remote control are widely known, and have been for some time. For example, simple autopilots fed by commercial Global Positioning System equipment would achieve most of the functionality needed to deliver a simple UTA to an area target.

Summary

The Unmanned Tactical Aircraft concept has the potential to become a new type of general purpose tactical aircraft system, with characteristics that are distinctly different from conventional piloted aircraft, UAVs, and cruise missiles. UTAs have the potential to bring unique elements of effectiveness and affordability to those air forces which deploy them. They will be able to perform missions that are difficult or inadvisable with piloted aircraft; achieve dominant performance in some aspects of air operations on the modern battlefield; exploit emerging breakthroughs in theatre information availability; and break the current cost paradigm, which is making it increasingly difficult for Western nations to maintain force structures under budgetary constraints.

Because of these characteristics, it seems that UTAs will be mixed cost-effectively with piloted aircraft in air force structures of the future, if technology bears its promise.

UTA is not only a concept for the far term. Many of the enabling automation and information technologies needed for UTA currently exist, and are being used in other military and commercial aircraft systems. The first UTAs could be operational in 5 - 10 years, performing a limited set of missions. Additional technology development will be required for the UTA to meet its full promise. This will probably not be achievable until the end of the 10 - 20 year time period. The concept will necessarily evolve over this entire time period, as new technologies become available, and the user community learns how best to operate UTAs and how to integrate them into the force structure as a whole.

Several individual technologies will be key to this development. However, the most important challenges are in the area of system integration - the UTA will not perform well in any time period unless it is thoughtfully integrated into a complete combat system. To this end, the involvement of users in conception, development, and demonstration of the UTA, as it evolves, will be essential.

8.2 Hypersonic Air-Breathing Missile

Continuation of the progress currently being made in development of hypersonic propulsion technology in several countries, both within NATO and outside, will make it possible to develop a high-speed, fast-response missile (Figure 8-3) propelled by an air-breathing engine, using storable liquid hydrocarbon fuels, and capable of fulfilling critical missions in reconnaissance, threat suppression, and strike, at an economically viable cost.

At the heart of the envisioned new missile Figure concept is the use of scramjet (supersonic combustion ramjet) propulsion[2]. Based upon

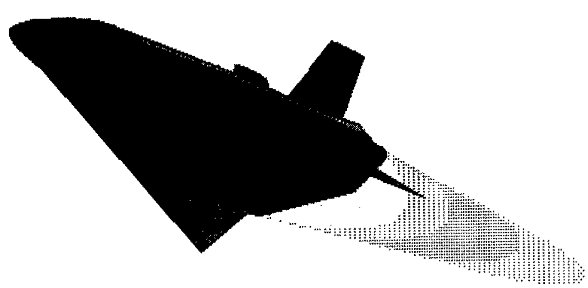

Figure 8-3: Hypersonic Missile Concept

[2] The essential technologies are discussed at greater length in Annex 5.

studies and extensive research and experimental work already carried out on various aspects of the propulsion technology[3], it can be projected that such a hypersonic air-breathing vehicle could fly at Mach 8 (2.4 km/sec) at altitudes up to 40 Km. It could have a (one-way) range in the order of 1500 Km, and have adequate payload capacity to carry a multispectral reconnaissance sensor and information relay package, or a hard target warhead and fusing package, within a size compatible with carriage and launch by tactical strike/fighter aircraft. With a solid rocket booster and a hydrocarbon-based fuel capable of storage without degradation for long periods, the missile would have minimal support requirements and virtually immediate readiness.

Missions and Capabilities

The distinctive attributes of the Hypersonic Air-Breathing Missile (HABM) - very high speed, large kinetic energy, long range, and immediate readiness - will make it an attractive basis for performance of several important military missions: very rapid air-to-surface attack upon transient surface targets (such as a tactical ballistic missile in launch phase); attack upon hardened targets; attack upon very high value airborne targets (such as AEW/C^3I aircraft, stand-off RSTA aircraft, and airborne laser "battleships"); and quick reaction reconnaissance.

In any mission flown through defended airspace or against defended targets, the HABM has two particular strengths:

- Its speed and altitude of transit to the target area make successful interception by most defensive weapon systems very difficult;
- The sustained propulsion of the missile leaves open wide freedom to vary its trajectory in ways that exacerbate the engagement problems of target area defensive weapons.

Transient Targets. Such a missile could be used for attack on high-priority, narrow time-window-of-exposure targets. In addition to the tactical ballistic missiles and their launchers mentioned above, other targets in this class might include high-value radar or weapon system installations designed for concealment/protection by withdrawal into hardened underground silos after firing. To be successful against such targets, the attack has to be delivered very quickly - ideally within less than the set-up time of the target system or, at worst, before the effective disappearance of the target system after it has performed its task or it has determined that it is under attack.

For illustration, consider a missile carried on a patrol aircraft approximately 400 Km from the target. The time elements of the overall target engagement cycle will comprise the missile flight time, plus the delay in target detection and recognition, the delay in targeting decision processes, the delay in formulating and communicating firing instructions to the carrier aircraft, and the delay in missile run-up prior to launch. With the advanced techniques and systems described elsewhere in this report, it is reasonable to postulate that the total of these latter delays might be no greater than 2 minutes. In this case, the total times elapsing from target presentation to missile impact would be as shown in the following chart.

The possibility of a successful attack on a transient target is clearly related to the target's time window of presentation. If a tactical ballistic missile launch cannot be detected until its booster is fired, the arrival of a counter attack, even five minutes later, poses little threat. However, in the future, the preparation process for such launches is expected to be detectable, and these and other transient targets will probably be vulnerable for times not less than 5 - 10 minutes. In these circumstances, the HABM will offer a decisive advantage over alternative stand-off weapons.

Deep/Hardened Targets. Targets of interest under this heading would include deeply-buried command and control centres and underground manufacturing and/or storage facilities for weapons of mass destruction. With a thick

[3] **References**

1. *"New World Vistas Air and Space Power for the 21st Century"*, Summary Volume, Aircraft and Propulsion Technologies Volumes, 1995, US Air Force.
2. *"Hypersonic Combined Cycle Propulsion"*, AGARD-CP-479, December 1990.
3. *"CFD Techniques for Propulsion Applications"*, AGARD-CP-510, February 1992.
4. *"Theoretical and Experimental Methods in Hypersonic Flows"*, AGARD-CP-514, April 1993.
5. *"Air breathing Propulsion for Missiles and Projectiles"*, AGARD-CP-526, September 1992.
6. *"Research and Development of Ram/Scramjets and Turboramjets in Russia"*, AGARD-CP-194, December 1993.

System	Approx. Minutes
Mach 8 HABM	4 - 5
Mach 2 conventional missile	15 - 20
Cruise missile (improved target input)	30 - 35

Elapsed time - Target presentation to strike

covering of soil and/or concrete, these targets are designed to be highly resistant to attack by conventional high-explosive weapons. However, they will, in many cases, be vulnerable to attack by a very high speed kinetic energy weapon.

To achieve the desired effect, the kinetic energy weapon requires a very high terminal velocity and a penetrator of high density and high strength. A steep diving approach to a target at Mach 8+ could offer very significant penetration capabilities, and, with a penetrator/vehicle mass in the order of 500 Kg, the HABM could be a very effective weapon. Guidance will not normally be a problem, since attack on designated geographic coordinates will usually suffice; and, for this purpose, GNS guidance can be used.

High-Value Airborne Targets. Used in air defence, a HABM could be a devastating weapon against extremely high-payoff airborne targets. Such a target set in the future might include JSTARS-type vehicles, airborne laser weapon vehicles, AWACS-type vehicles, or any of the family of carrier aircraft described earlier.

Quick-Reaction Reconnaissance. For some exceptional quick-reaction reconnaissance missions requiring a large radius of action, a hypersonic air-breathing vehicle offers several advantages as a sensor platform, compared with conventional air vehicles or satellites. These advantages are:

- Short transit time,
- Trajectory freedom not constrained by orbital mechanics,
- Relative immunity against conventional defences.

As an illustration, an air-launched hypersonic air-breathing reconnaissance vehicle could reach a target area at 800 Km range within 10 minutes of a decision to launch, and it could be recovered to a base in similar time. Moreover, the path flown in the vicinity of the target can be adapted within wide limits to optimise sensor performance.

Tactical Launch Platforms. Some consideration has been given to the installation parameters for carriage of this type of missile on typical strike/fighter aircraft, specifically the F-15 and F-16 aircraft. Both of these aircraft would provide suitable launch platforms; in the case of the F-16, one missile on a centreline station: in the case of the F-15, two missiles on in-board wing stations. Initial estimates for the missile put its weight in the range 1400 - 1600 Kg. This would provide a missile range capability, after launch, of 1200 - 1500 Km and a payload on the order of 100 - 200 Kg.

Figure 8-4 (following page) shows an artist's impression of an F-15 aircraft with two hypersonic missiles installed on its in-board launch rails. For maximum mission range, missile launch would occur at high subsonic to low supersonic aircraft flight speed, and at an altitude of 9 - 12 Km. The missile booster would rapidly accelerate the missile to scramjet take-over speed in the range Mach 5.5 - 6.0. If direct transition to scramjet propulsion is not possible, the air-breathing engine would have a dual-mode ramjet/scramjet capability during final post boost acceleration to a mission cruise Mach number of 7 - 8.

Design Considerations

Vehicle Configuration Issues. The airframe and engine design must be highly integrated. At high Mach number operation, the forebody is generally used as a compression ramp, while the afterbody plays a role in engine exhaust flow expansion and thrust generation, and therefore in the net thrust produced by the scramjet engine. A high lift/drag ratio aerodynamic-configured vehicles such as the "Waverider" concept may provide the best vehicle performance in terms of range capability.

The vehicle air inlet is an important component of a scramjet engine; in particular, inlet aerodynamic flow losses must be avoided or minimised. However, the main challenge for an air-breathing missile operating over a wide Mach number range is to limit the variability of the air inlet geometry during subsonic launch, transonic/supersonic

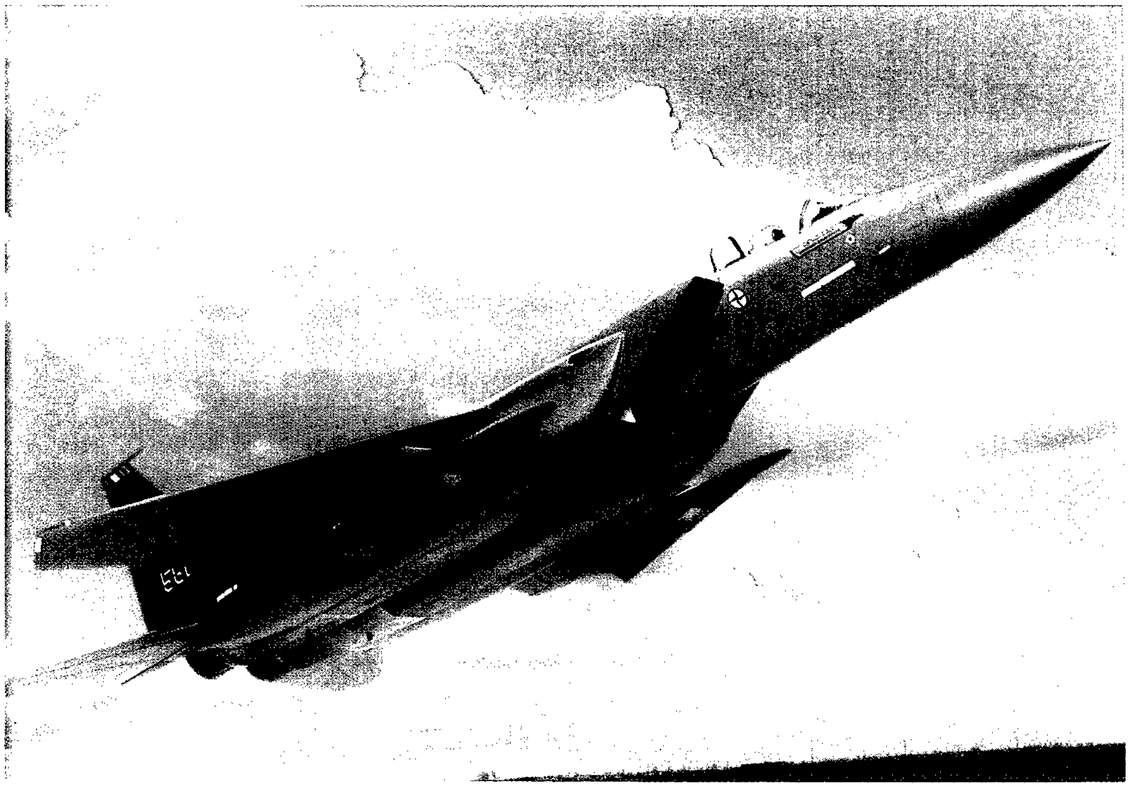

Figure 8-4: F-15 Equipped with Hypersonic Air-Breathing Missiles

acceleration and hypersonic cruise. Movable parts designed to sustain inherent high mechanical and thermal loads tend to be complex and heavy in weight, and therefore should be avoided. Additionally, an isolator duct between the inlet and combustor may be necessary to prevent inlet unstart caused by combustor pressure influences on inlet flow stability.

Propulsion. For the scramjet engine combustion chamber, the following important technologies must be considered: fuel injection concepts, ignition devices, combustion kinetics enhancement concepts, mixture enhancement devices, wall cooling techniques, and afterbody design concepts. All of these design technologies must be integrated into the overall scramjet combustion system. Additionally, for effective control of the combustion process in supersonic flows, the fuel must be introduced to the flowfield at various axial locations along the combustion chamber as a function of acceleration and cruise Mach number.

In order for the HABM system to be a viable weapon with minimally required logistics support, (sometimes referred to as having a "wooden round" capability) the system would require an easily storable fuel - a fuel that can remain onboard the missile for very long periods, even years. This could be either a solid or liquid fuel. For this missile system, a solid propellant would be used for the missile booster, while the fuel of choice for the scramjet-propelled fast-reaction missile would be a storable liquid hydrocarbon-based fuel possessing high heat-sink endothermic properties. Such a fuel can serve a dual function - supporting both thermal protection and combustion. For the thermal protection function, the fuel can be heated and decomposed by temperature via an endothermic reaction process, thus offering a cooling capability for the hot parts of both the air vehicle and the engine; hence, an endothermic hydrocarbon fuel can offer a significant advantage for this type of propulsion concept. The resulting total or partially gaseous decomposition products of the fuel are then injected into the combustion chamber and burned in the supersonic flow field. The main issue is energy management - how to effectively control the fuel flow to the combustor in order to cope with both vehicle/engine structural cooling and combustion.

A rocket booster is required. The scramjet engine will not operate at low-flight Mach numbers (subsonic and low supersonic); the rocket booster is used to accelerate the vehicle to Mach 3 (dual-mode ramjet/scramjet), or to Mach 5.5 (pure scramjet) to ensure entrance conditions to the combustion chamber that will sustain combustion. The principal issues then become integration between the booster and the scramjet combustion chamber, and transition between the booster phase and scramjet phase of operation. The preferred solution for the booster design would then be based on the technology offered by either a solid or liquid rocket booster concept.

Materials. Due to the severe operating environment of the scramjet-propelled missile during flight and the importance of low weight on overall system performance, use of new high-strength, high-temperature, and lightweight materials will be needed. This will include application of ceramic-matrix composites and coated carbon-carbon materials currently under development.

Thermal Management. Effective management of the thermal environment generated by the engine and airframe of a high-speed missile system during flight must be handled in an integrated global fashion - the principal task of satisfying the total cooling and thermal energy requirements of the system, within the limits of the resources available to that system. For high-speed flight, engine/airframe thermal management is the proper control of thermal energy which will provide acceptable structural, material and component temperatures throughout the entire flight. Coolant distribution systems (active cooling systems), passive thermal protection systems (insulation, ablatives, high-temperature materials, radiation cooling), and thermal/power transfer devices (heat exchangers, pumps) for all relevant airframe and propulsion system components, subsystems, and structures are included in the overall integrated vehicle thermal management system.

Target Detection, Guidance, and Tracking. High-speed interception of fast-moving targets requires accurate guidance and high manoeuvrability, especially in the terminal phase target. An on-board, Global Positioning System (GPS) based navigation system will likely be an integral part of the vehicle guidance system. Use of an auxiliary propulsion concept (e.g., lateral control thrusters) might also be considered, or perhaps a combination of both aerodynamic and auxiliary propulsion control during missile end-game operation may be required. It is recognised that target detection, guidance and tracking by the missile is largely dependent upon the specific target to be acquired and destroyed. For immobile targets, a precision navigation system will be required, but probably no specialised seekers and trackers will be necessary. On the other hand, for mobile targets just the opposite will be required. For purposes of this report, the specifics of terminal guidance and fusing will not be addressed.

Test and Evaluation. Test and evaluation requirements in development of a hypersonic air-breathing vehicle present formidable challenges[4]. Uncertainties in engine operability, survivability, and performance in the hypersonic regime drive the need for full-scale ground testing with run times on the same order as flight. Deficiencies exist in both scale and run time with current ground test facilities. The influence of scale on fuel mixing requires in-depth investigation. Characterising the thermodynamic properties and chemical composition of the test medium and its affect on propulsion is critical and should be accomplished early on. Verification of combustor turbulence and fuel injection and mixing models is also critical. A test methodology involving the fuel control and active cooling systems must be developed. Booster/ramjet/scramjet-mode transitions are critical, requiring specific facility operating conditions.

The strong coupling between inlet and engine performance in combination with the afterbody contribution necessitates a propulsion test facility which can accommodate an integrated inlet/engine/aft-body at full scale and at representative exhaust altitude conditions. Flight test of the airframe/engine subsystem may be a key risk reduction measure, requiring development of a host platform to achieve ignition and cruise conditions.

Affordability

Depending upon the weapon system capabilities required, the hypersonic missile technology development, demonstration and evaluation cost have been estimated to range from $500 - 1000M USD. The average unit production cost today for

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[4] See Annex 6.

a hypersonic missile system has been estimated at \$1 - 1.5M per unit; however, by taking full advantage of technology that has already been developed, it is believed that both development time and cost could be substantially reduced. Further cost savings will arise from system survivability.

Survivability, without the requirement for stealth, is enhanced by keeping the launch aircraft away from the heavily defended target area and by the near invulnerability offered by the hypersonic speed of the Mach 8 missile - a distinctive and important issue in terms of weapon system cost and affordability. This is not to imply that stealth-related countermeasures may be unnecessary for a Mach 8 missile. For example, should an airborne laser weapon be developed some day, even the hypersonic missile may require stealth provisions and reflective surfaces as added survivability countermeasures.

Affordability is further enhanced by keeping hypersonic missile cost competitive with that of current cruise missiles and by allowing a single launch aircraft to cover a footprint which would otherwise require numerous aircraft today.

Proliferation

Besides NATO Nations, Russia is pursuing development of this technology capability. The Russians have a Scramjet Flying Laboratory - a scramjet engine mounted to the nose of a rocket booster. This is strictly a "captive-carry" vehicle to determine scramjet engine performance under actual flight conditions (see Figure 8-5). As the technology is complex and highly sophisticated, and it requires long-term development and flight validation, the risk of proliferation of the technology beyond the high-tech Nations is considered to be moderate. However, once developed, variants can be expected to appear on the international arms market.

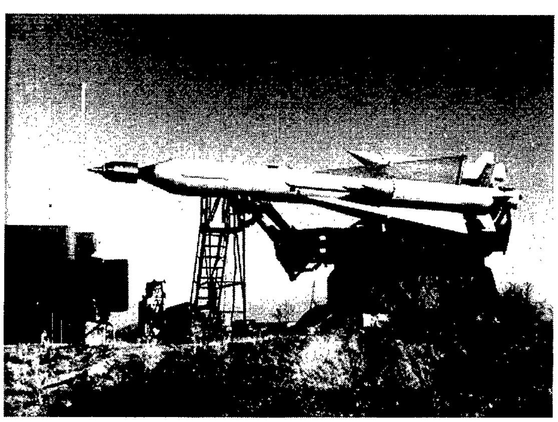

Figure 8-5: Russian Scramjet Flying Laboratory

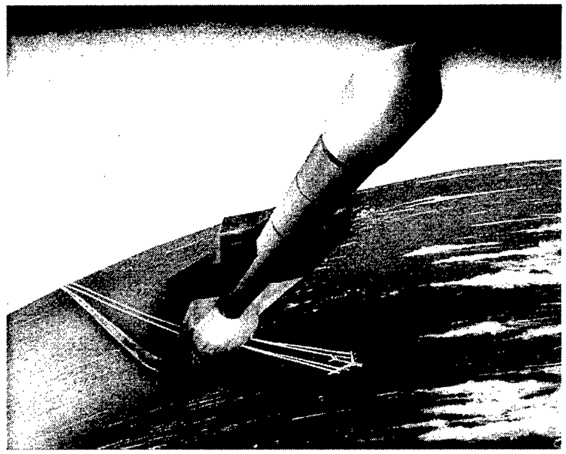

Figure 8-6: Scramjet-Boosted Satellite Launch

Dual Use

One area of potential civil use of scramjet propulsion is the commercial launch business as exemplified by the Orbital Sciences "Pegasus" launch system. Current Pegasus systems are purely rocket-propelled, and because of high launch weight limitations must be launched from a specially configured B-52 or an L-1011 aircraft. Application of an air-breathing scramjet system to replace the second stage rocket would nearly double available payload capability and permit vehicle launching from virtually any B-52 aircraft. Hence, non-defence use of this advanced air-breathing propulsion capability would be particularly attractive as a component of a low earth orbit satellite launch system (Figure 8-6). On the other hand, the cost and operational advantages of an air-breathing propulsion system for a small satellite space launcher may still not be as affordable as the current fully rocket-launched and propelled systems. The basic concept, however, continues to attract interest. It could, one day, become a cost effective and affordable solution to low earth orbit satellite launching.

Summary

By 2020 a Mach 8 speed range, air-breathing missile will be available. The key for achieving this capability will be the SCRAMJET engine. Such a missile will be capable of striking targets at a maximum range between 1200 - 1500 Km. It

will have sufficient payload for a variety of strike and reconnaissance missions, yet be small enough to be launched from a tactical aircraft.

8.3 Space Access

A new era is opening for space utilisation. In the fifties and sixties the race towards space reflected a search for expression of national pride and for military superiority. This political necessity overruled the cost issues. With the end of the Cold War, the competition was transformed into cooperation, as demonstrated by the Global Space Station. However, international cooperation is under constant threat of budget cuts. To try and reduce the cost of nationally funded missions, for scientific and other purposes, the tendency is to turn most space activities over to private business.

The goal is to make space activities profitable. This will create a race for commercial leadership, and that will require completely different space systems. Thus, although the reasons have changed, the quest for advanced launcher technologies remains a priority. In particular, reusable launch technologies will be developed in order to make access to space both cost effective and routine.

If this goal is attained, more space-based capabilities will become available to more and more nations. Several of these capabilities are addressed in this section. While NATO and the nations may choose not to avail themselves of those capabilities that tend to "militarise" space, other nations may not practice the same restraint.

Assuming a sustained technology development effort for civilian launchers, the timeframe anticipated for military operational applications, based upon civil demonstrator technology, is 2005 - 2010[5].

In the US, the Reusable Launch Vehicle technology demonstration programme comprises three demonstrators to be flown before the turn of the century:

- DC-X, a low-speed, vertical take-off, vertical landing rocket (Figure 8-7);
- X-33, an experimental sub-orbital vehicle;
- X-34, a small precursor experimental system.

The US expects to make a decision on the development of a full-scale next generation launcher before 2000.

Figure 8-7: The US NASA DC-X

In Europe, the FESTIP programme (Figure 8-8 following page) involves system and technology studies intended to select a system concept adapted to European needs, and to prepare for the development and validation of the technologies required for this system. The continuation of this effort beyond 1997 is planned to include hardware development and testing, as well as in-flight demonstrations with progressively increased ambitions. The plans are to prepare the decision on a full-scale development by 2005. France is also running a programme called PREPHA. PREPHA is focused on hypersonic air-breathing propulsion technology, which is relevant for future reusable launchers. An important German hypersonic programme produced the Sanger concept, which was recently integrated into the European FESTIP programme.

Russia is working towards the reduction of launch cost with its ORYOL programme. This programme contains both wide-ranging system studies, and technology development and validation. Although it runs with very little money (by Western standards), this programme has already produced some advanced results,

[5] Fuller details of the several national development programmes are contained in Annex 6.

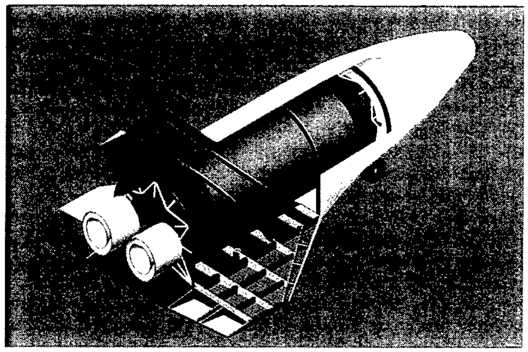

Figure 8-8: FESTIP - FSS Concept 13/14

including ground testing of components. No firm long-term plans are made, but the technical capability is there. Utilisation will largely depend on the political and economic near-term evolution of Russia. The unfavourable geographical situation of Russia's conventional launch sites, which requires a more versatile system, may prove a strong motivation.

Japan is steadily progressing with its predefined strategy towards independent access to space. Their HOPE-X vehicle is prepared to be launched and to return to earth by 2000. Although it is a shuttle-type vehicle, it will provide validation data for some key technologies needed for future reusable launchers. Propulsion is dealt with in a programme called ATREX, which contains ground and flight demonstrations. The intended use for the ATREX engine is not publicly stated, but it could apply to the propulsion of the first stage of a two-stage-to-orbit reusable launcher, or of any vehicle requiring sustained hypersonic cruise. Japan is also running system studies on an SSTO spaceplane.

These developments will create two primary opportunities for military use. One option will be reusable launchers as orbital vehicles: a lower-cost-to-launch, less infrastructure intensive, next generation shuttle. The second option is for a reusable sub-orbital vehicle, which would find its primary use as an RSTA platform.

Orbital Vehicles

The derivation of a military orbital vehicle from a civilian demonstrator would make near real-time global reach possible. The trajectories followed by the vehicle would require it to reach orbital speeds; however, the level of performance is still less challenging than for a civilian launcher.

While retaining the general design of a civilian demonstrator like the X-33, a launcher could be upgraded when improved technology becomes available. Up-sizing could yield a vehicle with a useful orbital payload, even on high-inclination orbits. Whether or not this condition could be technically met will depend on the basic vehicle.

Probably the most difficult challenge will be to attain and return from orbits of military interest, in particular the polar observation satellites orbit. This can be accomplished by in-orbit staging - the upper stage making the part of the mission from low-earth orbit, to high-altitude orbit, and back. The system still remains entirely reusable, since the upper stage can be brought back to Earth by the lower stage, or remain permanently in orbit ready (after refuelling) for later missions. The advantage of this concept is that the military functions can be concentrated on the upper stage, while the lower stage remains a simple cargo carrier, responding also to civilian needs.

The evolution of civilian demonstrators from sub-orbital to orbital may come naturally in the framework of a civilian launcher development. A civilian demonstrator cannot take advantage of all of the technology advances that will become available in later years for the full-size vehicle. However, retrofitting the vehicle with these advances could result in a vehicle with orbital capabilities. While such a small-scale vehicle would have limited commercial value, it could be an opportunity for the military. The vehicle would be civilian for experimentation; then, once upgraded, it would be available for military use. With deliberate planning, valuable synergy between civilian and military efforts could be obtained.

Reusable orbital vehicles could support a variety of missions. As reduced launch cost reduces satellite cost, a number of military functions, which, to date, have been more easily and cheaply performed from the ground, might become easier and cheaper to do from space - even if large numbers of satellites are required.

Extended Air Defence, Counter-Ballistic Missile Defence. An efficient extended air defence system from space requires a large number of participating satellites. It could be possible to include directed-energy weaponry for this mission. Although the beam needs to penetrate the atmosphere, it could be concentrated longer on an aircraft/cruise missile. Until now, cost considerations have been prohibitive.

Satellite Maintenance and Defence. Recovery to the ground would be feasible, if it were required. Satellites could also be replenished or repaired in situ. This capability could have a dramatic effect on the cost of future satellites because the number of functions and redundancy per satellite could be reduced if the satellite could be easily captured and returned to the ground, or refit in space. The same systems could provide the capability to defend space assets against potential acts of aggression.

In-Orbit Infrastructure. Space superiority has not been an issue so far, but could well become the next important challenge. Cooperation between space powers will become a condition for a viable space presence. Maintenance of permanent, or semi-permanent orbital structures would be vital to such a presence. Any military air mission is assumed to start from the ground and return to the ground. There would be an advantage to using permanently orbiting infrastructures and vehicles, and operating from and to space. Interventions to higher orbits would be possible from a space station. Orbit plane changes are possible by rebound on the atmosphere, allowing a real space manoeuvrability. This concept is interesting in that manoeuvrability is more easily achieved with small vehicles staying permanently in space, rather than with big vehicles coming from, and returning to, the ground; they could constitute a space relay of reusable launchers.

Counter Satellite. A reusable launcher will provide a number of options for dealing with an adversary's satellites. The options would range from blocking communications/observations by physically placing itself between the earth and the satellite, to capturing the satellite and returning it to earth, to neutralising or even destroying the satellite.

Space Cleaning. If it is attempted in the future, space cleaning will probably be limited to big objects that, during their long deterioration in space, create a lot of small objects. Space cleaning for peaceful purposes, if it becomes reasonably achievable, will involve the same means as selective military space cleaning.

Sub-Orbital RSTA platforms

Demonstrators or experimental vehicles could also be adapted as hypervelocity, sub-orbital RSTA platforms. The mission for these platforms would be to gather intelligence data on any given point of the Earth, at any pre-established time, with very short advance notice, and without need for any pre-deployment of ground forces. Key features would be that the observation is performed in sub-orbital or near-orbital conditions (120 to 200 Km altitude), that the vehicle is reusable for multiple missions, and that it operates like an aeroplane. Real-time data transmission is possible through a data relay satellite - possibly using optical links for security. The sub-orbital vehicle, unlike a satellite, could be reconfigured from one mission to the next. The reusability of the vehicle for multiple missions, and its aeroplane-like mode of operation mean that the utilisation cost would be comparable to aircraft operations - orders of magnitude below the cost of the launch of a single spacecraft for a single mission.

This RSTA platform would not be subject to the limitations of satellites. Satellite systems are constrained by orbital mechanics; the time of the observation cannot be pre-selected. For a limited satellite constellation, orbital mechanics allow an adversary to establish time tables of the satellites' passage over sensitive targets. The driving factor for a satellite system is the continuity of the observation capability. If permanent coverage is a strong requirement, then a large constellation of satellites needs to be maintained permanently. Where only one or a few satellites can be afforded, it may be necessary to wait a day or more before the best observation conditions are met. The sub-orbital vehicle could be a viable option for a nation which wanted the capability for single, time-critical observations, but did not have access to a large constellation of satellites.

The usual distance of observation from a satellite is of the order of 800 Km. Most observations are done laterally at greater distances, which limits their resolution. On the contrary, the distance of observation for a sub-orbital vehicle can be as low as 100 - 120 Km, exactly abeam the target to allow optimal resolution. From the sensors point of view, observation from low space eliminates the problem of aerodynamic heating, despite the hypervelocity of the vehicle.

Due to the very short time allowed for its observation, and due to its sub-orbital, high-speed trajectory, a sub-orbital observation vehicle is very difficult to target accurately. It is manoeuvrable, even outside the atmosphere, and it flies too fast to be shot down with existing

means. It would take the development of an extremely high-performance exo-atmospheric antimissile system to threaten it. Unlike a ballistic missile, its trajectory does not designate its target; and its parameters are difficult to determine, since the propulsion can be active while flying over the target. From the standpoint of international law it would be a space object, thus it could operate without entering unauthorised national airspace.

Affordability

Military forces will have two options for using future reusable launchers, whether orbital or sub-orbital:

- As customers for commercial systems, there would be, for this purpose, no military specific development cost; the earliest timeframe is 2010 - 2020;
- By adapting civilian demonstrators. This would require only limited development efforts to account for different military operational requirements.

Since profitability for reusable launchers can only be attained with large number of launches, commercial operators are expected to welcome military customers. Provided they are clearly known, specific requirements of military users could be taken into account early in the development phase of civilian launchers. For example, if dimensioning requirements result from military needs, they can be assessed from a global profitability point of view.

The resulting commercial systems could offer the following advantages:

- **Reduced launch cost**. The objective is to reduce the recurrent specific launch cost by a factor of at least three - compared to expendable launchers in the European FESTIP programme; by a factor of ten - compared to the Shuttle cost in the US RLV programme; and even by two orders of magnitude in the US and Japanese second-generation, air-breathing launcher studies;
- **Launch almost on demand.** Reusable launcher availability should provide greater scheduling flexibility;
- **Capability to service in-orbit, or retrieve to ground, failed or ageing satellites.** As mentioned above, this capability will induce a paradigm shift in the design of satellites. Presently, there is great pressure in the design and qualification of satellites to guarantee their full functionality for several years. If a simple and cheap capability to fix or replace failed satellites appears, the requirements concerning the lifetime and reliability of the satellites will become less stringent. This would lead to a reduction in the size of satellites, and to a reduction of the qualification efforts needed. The reduction in size will, in turn, have an effect on launch cost and a snowball effect on spacecraft cost. A new generation of satellites may appear, much simpler than their predecessors.

The military space missions described in this document would use civilian ground infrastructures. This is the most efficient and cost-effective system-level option.

Proliferation

Whether or not these possibilities are taken up by NATO, it has to be borne in mind that the emergence of new commercial launchers will generate new types of threats.

Initially, the sources of such technology will be very restricted. Based on civilian developments, the military capabilities addressed in this document are expected to be within reach by 2010 - 2020 (assuming a sustained development effort) in the US, Europe, Russia, Japan, and potentially, China. The proliferation of these technologies is severely limited by the technical complexity and the development cost of such systems. However, with mutual assistance between countries, or by the will of a nation's leadership, these political or economic impairments could be quickly overcome.

Reusable launcher proliferation to small countries is not expected, at least not until the services or the vehicles themselves are put on the open market. A desperate search for commercial benefits or foreign currencies may be a factor of proliferation. Of course the independent operation of one of these vehicles is not straightforward, but some countries, such as India and Israel, already have some operational experience in orbital launches. There is the significant potential that the operational knowledge necessary to use these vehicles can be bought like any other mercenary

capability today, and the procurement cost of these vehicles is not an obstacle.

Conclusions

As the new technologies developed for commercial launchers become available, it will be possible to take advantage of them to develop specifically military applications. In terms of technological challenge, commercial reusable launchers are much more ambitious than their possible military counterparts. As a direct consequence, military applications are expected to be feasible well before the commercial launchers are actually made operational. Specifically operational military applications can be found for vehicles that are not able to reach orbital velocity, and/or which have a payload capability below commercial standards, and/or which have a limited lifetime and reliability. In order to be profitable, commercial launchers need all of these attributes, and require a payload, up and down, on the order of several tons. The difference in technical challenge can be very important. For an orbital launcher, the last few metres per second of performance are exponentially difficult to obtain, exponentially more expensive, and may not be required for some military purposes. There could be an order of magnitude saving in the technical difficulty, size, and cost between the civilian vehicles and those which could satisfy military needs.

The military usefulness of these vehicles will be increased if the military requirements are taken into account early in the design process. This is also in the interest of the civilian operators, who need to develop as large a customer base as possible. In any case, the drastic reduction of cost, the increased flexibility of launches, and the new opportunity to return a satellite to the ground will create a revolution in the military use of space.

8.4 Summary

The realisation of these new concepts will confront NATO with an entirely new set of capabilities, as well as a new set of concerns.

The UTA vision is of a weapon system which expands tactical aircraft mission options by eliminating the risk of casualty or capture of air crews, and by performing new kinds of missions more effectively than conventional piloted aircraft. They are envisioned to be a class of air combat vehicles with performance characteristics tailored to enhance mission effectiveness, rather than to meet the physiological needs of an air crew. UTAs will become integral parts of the air forces of many nations during the next 25 years.

The application of Scramjet propulsion to hypersonic missile weapon systems offers improvements in responsiveness, survivability, and affordability. Such a weapon, when launched from current tactical aircraft, bombers, and/or ships, could strike targets 1200 - 1600 Km away within 10 - 15 minutes. It will provide a cost effective means of providing accurate, virtually immediate strike response to crisis situations throughout the NATO area of interest.

Commercial forces will drive the development of reusable launchers for space access. These launchers will provide opportunities for reduced-cost routine access to space. Orbital vehicles will provide capabilities to extend the area of influence into orbit. Additionally, sub-orbital vehicles will provide very short notice (within one hour) RSTA of any point on the globe from the outer edge of the atmosphere.

Taken together, these systems alone will provide future leaders with the ability to "see" into a crisis area and to strike, if required, in less than an hour. Within 24 hours, an unmanned military presence could be in place to establish and maintain air superiority. In combination with systems described in Chapter 7, future military forces could have an unprecedented capability for deterrence, and when deterrence failed, an unprecedented ability to dominate any future battlespace. The limiting factor will be cost.

9. COST

Perhaps the most severe challenge confronting the NATO defence community is that of maintaining adequately large, effective, and versatile defence forces to service current requirements and still meet possible future needs within the immutable constraints of national defence budgets. From the technological point of view, this challenge is just as great as that involved in times past, when the ultimate in operational performance was the goal, but the set of parameters to be considered in the course of optimisation is probably larger, and certainly more heterogeneous.

This chapter illustrates the broad ramifications of this problem; beginning with a description of the elements of life-cycle cost, going on to describe some techniques for controlling costs, and for reducing costs. The US Joint Strike Fighter program is presented as an example, and the chapter concludes with an enumeration of the principles of life-cycle cost reductions.

9.1 Elements of Life-Cycle Cost

The overall cost of an aerospace vehicle or system has several major components - notably the cost of acquisition (development plus production), the cost of usage (replenishment plus maintenance),

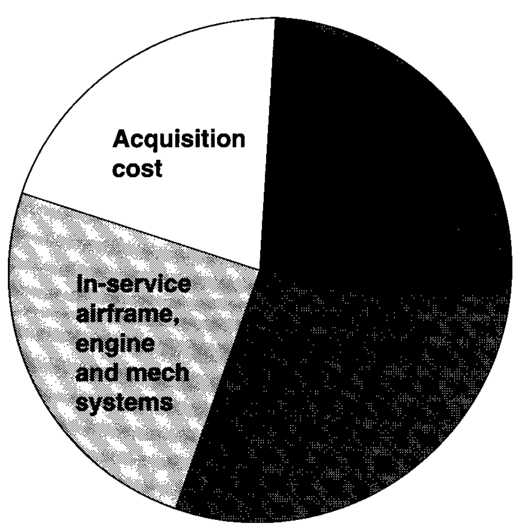

Figure 9-1: Life-Cycle Costs for a Manned Combat Aircraft

and the cost of the human operators (pilots, controllers, et cetera), including training costs. Figure 9-1 shows some illustrative data for the materiel elements of a manned combat aircraft.

Historically, acquisition cost has been a major factor determining whether a new combat aircraft will be procured. However, it is clear from the chart that this may be only a modest proportion of the total life-cycle cost. Indeed, with an increasing trend towards life extension of existing systems, the balance is likely to shift further toward in-service costs being the most dominant factor.

A further point to note is that decisions that determine the magnitude of in-service costs are made at a very early stage of the design process, as illustrated in Figure 9-2 (following page). For example, it has been estimated that, by the time that the design of a manned combat aircraft is frozen, as much as 90% of the life-cycle costs have been effectively predetermined.

Much of technology's contribution to solving this problem will lie in the ever-increasing power of computation and, hence, in our ability to model and predict all aspects of cost and performance at an early stage of the design and development process. Cost may then be included as a parameter in the design optimisation process, so that an appropriate balance between life-cycle cost and operational performance can be delivered to specification.

9.2 Cost Control Techniques

Synthetic Environments in the Planning/Procurement Cycle

Synthetic environments[1], in simulating the use of all equipment employed, will support the whole requirement, research, development, and procurement process. At all stages of the process, it will be possible to test the equipment being developed in a realistic simulation and, along with expected developments in other equipment being modelled at the same time, to provide appropriate external inputs. This will give much more realistic results than available in previous computer simulations, to include easier set-up and

[1] See also Annex 2.

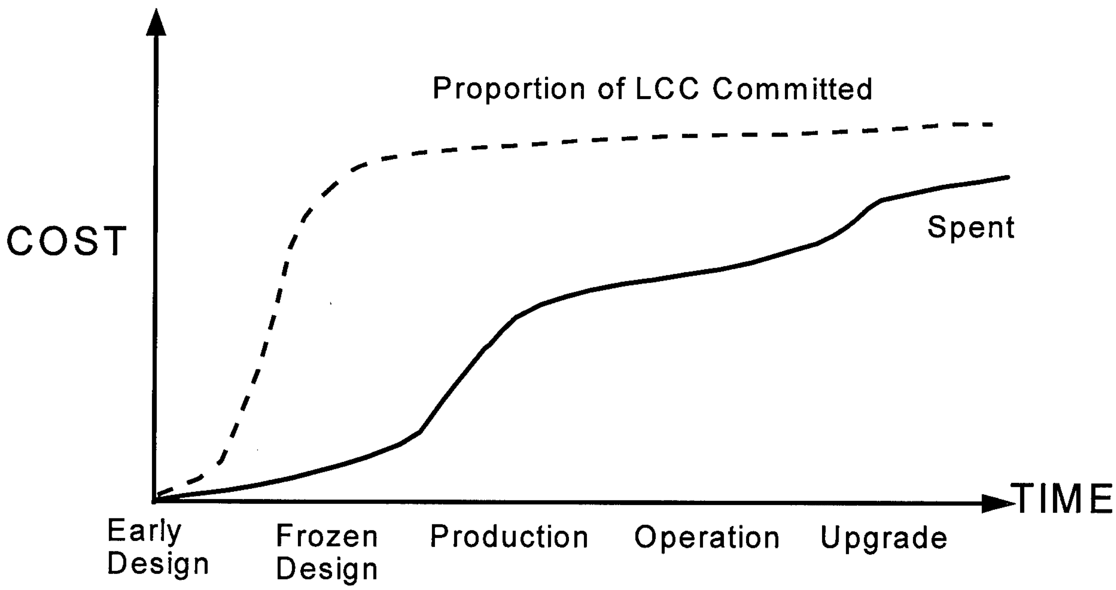

Figure 9-2: Cost Commitment and Spend Through System Life-Cycle

calibration. Of particular value is that military operators will be able to be involved at all stages of the procurement process, not just in providing an initial requirement and a final test of procured equipment. By keeping the operator involved at all stages of a system's development, the full implications of trade-off decisions can be better understood by both the user who needs the capability, and the developer who is trying to meet the requirement in the most cost-effective way. Simulation will allow the operator and the developer to see "for real" what the effects of trade-offs will be, in terms of both costs and military effectiveness, provided the simulations are reliable.

This will result in dramatic changes in planning, development, and operational processes, including:

- Development of requirements and concepts of operation;
- The design process, through to development, manufacture and testing;
- Training for operational and logistical purposes;
- Military requirements and their cost effectiveness;
- Operational force deployments, rehearsal, war plan development and logistics planning.

Because synthetic environments will enable the design and test of commercial and military systems in a virtual world, they could contribute, together with other technologies on a longer time horizon, toward advanced "just-in-time" manufacturing capabilities. With such capabilities, advanced designs could be kept up-to-date with the most current technologies; however, production of these advance systems could be deferred until required by some change in the world situation. Pursuing standardised synthetic environments could have profound implications for the relation between NATO governments, their defence organisations, and the commercial sector that currently produces the needed military equipment. Close cooperation between all three sectors will be necessary to ensure that the development and application of this technology will produce the desired structures, and not the loss of vital military production capabilities.

Synthetic environments will provide a software environment that will allow the user, in an integrated fashion, to:

- Investigate new and alternative solutions at low cost, including the potential for, and implications of, reducing manpower (crew) in a particular vehicle or system;
- Exploit traditional simulation capabilities (aerodynamics, flight mechanics,

et cetera) to define a design and evaluate its performance;

- Model the entire production process, allowing the assessment of the implementation of technological advancements. Effectiveness versus cost trade-offs will be easily provided to decision makers;

- Access a common data base, which will allow the standardisation of the design approach.

It is expected that acquisition decisions will be justified and documented through life-cycle simulation. In systems development and acquisition, we will see a continuation, expansion, and improvement in the use of synthetic environments in the weapons system development process. Some programmes today are trying to make synthetic environments an integral part of making and documenting systems decisions during requirements development and system evolution, to ensure that life-cycle costs are affordable[2]. By 2020, we should be able to model and simulate the entire life cycle of a system, so that decisions made at early stages (whether political, programmatic, operational, or technical) can be evaluated rapidly in an operational context to determine their implications.

Optimisation

Designing a modern, high-performance aircraft is a complex process with inputs from many disciplines, and the finished product is a compromise between conflicting requirements. Inputs and aspects from many technical disciplines must be taken into account, in order to arrive at an optimum structural design. To ensure that the final design meets all specified requirements, it is essential that the design engineers have access to both reliable analytical design tools and accurate definitions of the operational design loads experienced by the aircraft within its flight envelope. In the structural design process, application of advanced aerospace materials and consideration of aeroelastic effects, in context with the overall structural integrity, play fundamental roles. The emphasis on aeroelastic considerations has drastically increased in the past four decades. Structural design philosophy today recognises aeroelasticity as a primary design parameter.

Virtual Manufacturing and Concurrent Engineering

In recent years, the emphasis in design has turned to concurrent engineering aspects, design for maintainability, accessibility, and virtual manufacturing. This technique uses all necessary material, manufacturing, and machine data right from the beginning of the design. It can be demonstrated that a fully automatic Numerical Code generation can already be achieved at the end of the engineer's design process, producing verified manufacturable data without any additional human interaction, based on the designed geometry. Time-consuming iteration loops coming back from the manufacturing phases and creating local iteration loops to the structural analysis are avoided. Real examples of this "virtual manufacturing" process are indicating 10 to 50 times faster processes compared to existing methods.

The virtual prototype simulates the topography of the structure, controls, systems, et cetera, and of course, the performance of these aspects. It naturally mimics the disposition of all of these components, their non-interference, and their accessibility for manufacture, servicing, and repair. All of the components will have attributes assigned to them, so that costs can be evaluated in advance and fed back into the optimum design wherever possible.

One of the component parts of the virtual manufacturing simulation is that of virtual processing, or numerical simulation, of metal, polymer, and other material processes. The need to cut costs will mean much more use of metal and composite manufacturing processes, whereby the structural properties depend on the history of the process, and may differ from component to component.

Test by Analysis

It has been traditional to analyse structures (by the Finite Element Method, for example), and to use the delivered stress fields to then predict failure by using data sheets, look up data bases, et cetera.

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[2] An overview of the application of the synthetic environments concept to the US Joint Strike Fighter programme (JSF) is given in *"Modelling and Flight Simulation - Tools to Produce Affordable Weapon Systems"*, Keynote paper by Gen. G. K. Muellner to AGARD FVP Symposium on *"Flight Simulation - Where are the Challenges?"* May 1995.

All of these data bases will have been based on test. Such tests are extremely expensive, and it is now becoming more and more necessary to rely on numerical simulation to predict failure as well. Such simulation is almost inevitably non-linear, but codes have become more user friendly in this regard, more robust in tracing failure modes and paths, and of course, the computing hardware needed for non-linear analysis is now affordable as a design tool. Large cost savings can be expected by avoiding the component and full-scale static tests of aerospace structures. Safety factors of 1.5 on extreme load values need to be replaced by approaches that take account of the stochastic nature of events, material properties, and structural dimensions. Probabilistic approaches can learn much from the design of off-shore structures, which have very similar features and environments.

To be fully effective, any approach to reduction of the life-cycle cost of a system must give attention both to the over-arching performance requirements and specified pattern of usage for the system, and to the design, development, and manufacturing methods used to produce the system. In all aspects, cost must be treated as a primary design parameter.

9.3 Cost Reduction

This section concentrates on the improvements in structures and materials, and in their design and use, that will lead to reduced costs. The improvements and trends here will be more substantial and widely spread, fuelled largely by the growth in computing hardware, software, and networking, so that the main cost savings will be in lower manpower levels and much quicker design, evaluation, and production. However, performance improvements will also be anticipated[3].

Smart Structures Technology

Development in disciplines such as sensing technology, computation, control, micromechanics, materials (including processing), and many others has made significant progress during the past decades. This progress has been mainly possible through an in-depth analysis of the different aspects in these disciplines. To consequently take more advantage of this progress, a synergy between these different disciplines has to be established, resulting in what has been termed to be smart materials and structures. Briefly explained, smart (alternatively: active, adaptive, multifunctional, or intelligent) materials and structures is the integration of sensing and actuation elements into a structure or, even more ambitiously, into a material, with sensor and actuator being linked by a controller. Materials actually favoured for integration include optical fibres and piezoelectric materials, shape memory alloys, and electro-rheological fluids with respect to actuators and microprocessors, neural networks, fuzzy logic, and various types of signal processing with respect to control. Since performance of military aircraft and spacecraft has progressed in a sequence of steps in the past, smart materials and structures technology can thus be considered to be a next step in enhancement.

Basic Materials

Materials are a key technology to achieving high performance for virtually all products. While performance improvements, such as high-temperature mechanical properties, should be a primary thrust, affordability also has to be included, from the beginning, in R&D goals. The performance improvements needed in engines, including increased thrust and better specific fuel consumption, will inevitably mean much higher combustor temperatures, and generally more severe environments, for engine materials. Targets of a thrust/weight ratio of 20:1 and a specific fuel consumption of 0.6 per hour are conceivable. Airframe materials for high Mach number missiles and aircraft likewise require improvement in high-temperature materials, but for the most part, airframe needs are for lower density, higher stiffness and strength, and modest temperatures (under 350° F). Research and development are needed in advanced fibres, enhanced resins, lightweight metals, metal-matrix composites, ceramics, ceramic-matrix composites, carbon-carbon, functionally graded materials, insulations, and coatings.

Ceramics, CMCs (Ceramic-Matrix Composites), and Carbon-Carbon are a very important area for future high-temperature material research for high-speed vehicles, and for engines and their environment. High-performance fibres are needed

[3] The major developments to reduce acquisition costs are described briefly here; a more extensive description can be found in Annex 10.

to survive processing and elevated temperatures without degradation. Low-cost ceramics and processes, such as the overlay form consolidation of glass ceramic-matrix composites, need to be developed. Enhancements to carbon-carbon, for higher performance and lower cost, need to be developed.

The options for engine materials in particular, will be driven by temperature in addition to the usual needs. Intermetallics will have a role, since they are cheaper than CMC. Ti-Al, with boron-based doping for better toughness, is the lightest, but will be limited to 900° C. Ni-Al and single-crystal Ni Aluminides may go beyond 1100° C, but are heavier. For temperatures in excess of 1600° C, CMCs seem the only solution. SiC-SiC looks unlikely to overcome the oxidation problems, so probably AlOx-Ox, using chemical infiltration, will be developed. Targets should be 400 MPa ultimate tensile strength, with no creep for 2000 hours.

Functionally graded materials (FGM) is an embryonic technology that is being aggressively pursued in Japan, and should be a very significant topic by 2020. The ability to tailor material properties through the thickness to meet specific application requirements, allows optimisation and durability of FGMs. In the longer term, the ability to tailor the full range of material properties throughout the component or structure will remove the current distinction between material selection and structural design. Through biomimetics, we will learn to optimise material microstructure in the context of the macroscopic structural constraints. The ultimate, and perhaps unobtainable, goal might be to specify each atom or molecule, and its bonding to neighbouring atoms, in such a way as to optimise the performance of the entire structure.

New lightweight, high-performance insulation materials are needed. The advent of broad use of liquid natural gas for a variety of applications will, alone, drive this need. Carbon fibres insulation and the "Starlight" material appear promising, but need optimisation and commercialisation (particularly Starlight). Modelling and simulation could play a major role in insulation material optimisation.

Coatings and smart or passive, low-observable materials in all frequency ranges (electromagnetic, infra-red, visible, et cetera) are an important R&D area. A significant amount of progress has recently been made in low-cost diamond coating, allowing high deposition rate/low pressure diamond coating. The mechanical and physical properties of diamond make this work very important, since diamond coatings offer the opportunity to significantly enhance material strength, durability, abrasion resistance, hardness, lubricity, thermal resistance and conductance, and to vary electrical resistance/conductance. A broad range of applications should be explored, including modelling and simulation work to optimise the coating and processing.

Manufacturing

Manufacturing technology and quality are an integral part of materials and structures R&D. Concurrent Engineering/Integrated Product-Process Definition have already been addressed, mandating an integrated approach in R&D that results in affordable technology for improved products.

Automated processes, on-line NDE and process control, and use of embedded sensors for process monitoring/structural health monitoring/defect detection permits implementation of an Embedded Quality philosophy, with no subsequent inspection required after fabrication. This approach provides high-quality, low-cost parts, with self-contained quality/structural health monitoring. Alternate NDE approaches to inspect components in assembled structures need to be developed.

Information Systems

Life-cycle costs of information systems are likely to be reduced as a result of technical improvements and commercial developments. The implementation of integrated modular avionics as open systems will not only reduce acquisition cost, but also life-cycle costs, since system upgrades will be cheaper. The affordability of unmanned air vehicle and satellite communications development and deployment should also benefit from a number of features including:

- Commercial activities of the direct broadcast service;
- The continuing advances in micro-miniaturisation, power generation,

et cetera, which can lead to smaller, lighter and, therefore, cheaper payloads;

- Use of smaller launchers.

Similarly, many fixed facilities, and some mobile/airborne C^4I assets, should be able to make increasing use of Commercial-Off-The-Shelf (COTS) hardware and software. Additional cost benefits can be expected from the development of hardware and software for automatic processing, screening, and exploitation of the large amounts of data expected in 2020. Software engineering is a vital problem that must be monitored carefully. The implementation of modular object-oriented software techniques will reduce costs.

Reduction of Operating Costs

The cost of fuel is already having some impact on aircraft usage by NATO forces. It has been shown that 20 - 40% of typical weapon system life-cycle cost is due to the engine, plus fuel required, during its operating life. The impact upon life-cycle cost is likely to become much more severe in the period to 2020, because of major increases in energy costs. Consequently, advanced technologies in engine component design, manufacturing, and performance capability will have a substantial impact on the life-cycle cost of any weapon system[4].

Materials, design concepts, and technology that can reduce airframe and engine weight and improve performance must be developed to minimise fuel costs. For example, the application of composites to the wing of a small twin-jet transport aircraft is estimated to produce approximately 6% in fuel savings. Also, the cost savings attributable to materials and structures will become more important as times between aircraft renewals increase. Corrosion, fatigue damage, and wear and tear are major issues for ageing aircraft, which are now being used significantly longer than previously envisioned. As repair and replacement become more common, better and less expensive methods of inspection will be needed. Preferably, these will use robust, user-friendly technologies. Hidden corrosion can lead to catastrophic failure, due to corrosion-fatigue interaction. Since it can currently only be detected by expensive tear-down inspections, the US Air Force has indicated that developing non-destructive inspection methods to detect hidden corrosion is their number one technology priority for ageing aircraft. A whole battery of non-contact ultrasonic and thermal scanning, and in-contact vibration and stress-wave techniques, will be brought to maturity, enabling quick global scans to be followed by local, more precise methods for both metal and composite structures.

Maintainability Improvement

The importance of maintainability is demonstrated by the fact that a considerable fraction of the oldest aircraft in most Air Forces is grounded at any given time. These aircraft are in depot undergoing repair of corrosion/fatigue - a huge cost and operating burden to an Air Force. The techniques referred to above will reduce much of the degradation familiar to the airforces of the 1990's. Better damage tolerance will also reduce repair costs and downtime. It would be a huge cost saving to have a maintenance-free aircraft, even if the acquisition cost were higher as a consequence. In principle, this goal is not impossible, but the only way to have even a near maintenance-free aircraft would be to build in excess redundancy and switch load paths via smart sensors. The weight penalty of such an approach would be excessive. The only realistic course is to continue to improve maintainability.

Thus the materials and structures used in aerospace vehicles must be designed for maintainability - primarily corrosion resistance and durability as mentioned, but also repairability[5].

9.4 The Joint Strike Fighter Example

An illustration of the extent and power of such a coordinated approach is provided by the US programme to produce a Joint Strike Fighter (JSF). Overall, the aim of this programme is to provide a family of aircraft that can meet a wide range of multi-service needs with a high level of operational effectiveness, and with a potential saving of life-cycle cost in the range 33 - 55%, relative to contemporary experience of comparable designs.

[4] See Annex 8.

[5] See Annex 10.

To achieve this goal, the programme relies upon a combination of measures:

- Refinement of the operational requirement by a "system of systems" approach, including consideration of the use of alternative assets (land, sea, or air) for performance of each specified mission, and treating cost goals on the same footing as performance goals;
- Application of improved technology to reduce the time and cost of development, manufacture, and support;
- Streamlined acquisition procedures;
- Multi-service buy, yielding benefits of scale.

To measure and control contributions to the process of life-cycle cost reduction, the JSF Program Office has established quantitative targets for various technical areas. These targets, which are shown in Table 9-1, are indicative of the scope currently seen for realisation of life-cycle cost savings.

9.5 Summary

As a result of experience with various programmes such as the JSF, a new philosophy toward life-cycle cost reduction is emerging. This philosophy is revolutionary in its approach to the military acquisition process. Today, and for the foreseeable future, new systems cannot cost much more to acquire, own, and operate than the systems they replace. This philosophy is expressed in eight principles:

- Treat cost as a primary design parameter;
- Take both production and operational issues fully into account at the design stage;
- Introduce new or advanced technologies only if they can "buy" their way in - that is, if the tangible benefits of their use, through higher performance and/or reliability, more than outweigh their additional cost;
- Facilitate systems integration through use of open avionics and software architectures;
- Use concurrent engineering approaches to minimise development cycle time and acquisition cost;
- Design vehicle families to perform multiple missions with moderate changes e.g., a multi-role fighter family;
- Look for new concepts of operation, shifting missions to lower cost platforms e.g., substitution of unmanned for manned aircraft;
- Exploit commonalities with the civil market, e.g., in the transport sector or for space access.

These general principles can be portrayed, alternatively, in terms of tailoring system specifications. In this perspective:

- Tailoring the specifications means negotiating the mission requirements, acquisition requirements, and manufacturing specifications to give the designer, programme manager, and manufacturing manager as much freedom as possible;
- Mission requirements should be resolutely limited to what is actually needed; no elaboration of the requirement should be accepted without thorough trade-off studies of the costs and the benefits of such elaboration;

Area of Endeavour	LCC Reduction Target	Relative to
Structures and Materials	30% (with 20% mass reduction)	F/A-18 E/F
Sub-system Technologies	4%	F-22
	12%	F-16
Avionics Technology	9 - 17%	F-22
Manufacturing	12 - 20%	Conventional Approaches

Table 9-1: JSF Life-Cycle Cost Reduction Targets

- Mission requirements should also be balanced, so that the resulting system design is not overwhelmingly driven by one particular requirement. In addition, the portfolio of mission requirements should be negotiable and changeable, as the costs of meeting the various requirements become better known.

Tailoring the manufacturing specifications means allowing the manufacturing group to define the material and process specifications, to be party to establishing tolerances, and to be empowered to adopt best commercial practices.

The cost of NATO air forces over the coming decades will be made up of the slowly declining cost of currently in-service aircraft and the rising cost of the growing complement of replacement aircraft. To live within severe budgetary constraints, NATO forces will need to:

- Review their statements of need for aerospace vehicles, weapons, and systems, to ensure a balanced, but minimum, sufficiency to meet currently recognised and prudently foreseen military needs;

- Adopt methods of specification, design, development, production, operation, support, and disposal of its aerospace materiel that will minimise the cost of ownership for the required level of military capability;

- Take a strategic view of the makeup of their air forces as a whole, aiming to achieve the maximum economies that may be derived from multi-role capabilities of individual aircraft and a high level of commonality in manufacture, logistic support, and training;

- Carefully evaluate the balance between the specified characteristics of aerospace materiel, its military effectiveness, and its cost of ownership, in order to secure the maximum of military effectiveness, in the envisioned range of operational situations, per unit of defence money expended.

ANNEX 1: COMMUNICATIONS ELECTRONIC WARFARE/DEFENCE

Communicating information (voice, message/data, graphics/images) is, and will remain, a most vital aspect of command and control and therefore, of warfare. EW against communications will thus continue to be the focus of much research and development.

The enormous developments in digital signal processing (DSP) and semiconductor RF technology during the last decades has generated many novel disruption techniques and enhanced more classical ones. These developments have, of course, also enhanced the technologies of protection. The development of nuclear weapons has resulted in the feasibility of disrupting electromagnetic wave propagation by detonating such weapons at high altitudes. Such detonations require sophisticated capabilities, but they can have devastating effects on radio/SATCOM systems.

Another revolution in communications has been through the development of photonic/fibre-optic/light-wave techniques. For fixed terrestrial communications links it is now possible to state that capacity is no longer a problem, if fibre-optic links can be set-up (switching, delivering the capacity to individual small users is, however, still a bottle-neck). A similar revolution in wireless/radio communications is not anticipated in the near future. Wireless/radio communication will be the essential element of all tactical operations and a significant component of higher level command and control (C^2) requirements, while also becoming increasingly more important for the civil/commercial sectors. Therefore, protecting such communications from electronic (and of course physical) disruption is essential.

Terrestrial, hard-wired (telephone wires, coaxial and fibre-optic cables) transmission media and the associated switching systems have to be protected against, primarily, physical destruction and natural/man-made electromagnetic disturbances/events. Although fibre-optic links have inherent protection from externally coupled disturbing signals, there are other electronic warfare/defence issues relevant to such terrestrial communications such as electromagnetic pulse effects, but these will not be covered here for brevity.

A recent development born out of the computer and related DSP revolution is the vulnerability of communications systems to software attacks such as viruses, worms, et cetera. Such attacks can be dormant and timed to activate at some time instant, be triggered by some action, or can be propagated electronically through the increasingly richly connected networks. Although such class of attacks on communications are important, and will be more so in the future, they are, for the present at least, more appropriately covered in software-related fora.

Military/National Security (M/NS) related procurements are becoming an increasingly less significant portion of the Communication and Information Systems market, in marked contrast to a few decades ago. For example, only two decades ago M/NS research and development dominated the satellite and computer areas. This is no longer the case. As a result of this and continuing decreases in available funds, M/NS communities must increasingly rely on COTS products. This development can be anticipated to have the effect of dispersing technology much faster than in the past, with concurrent risk developments.

Radio communications **electronic warfare (EW)** or **electronic defence (ED)**[1] can be treated from a number of perspectives:

- Source signal:
    - Analogue or digital speech,
    - Asynchronous or synchronous digital signals/data.
- Distance, terrain limitations:
    - Line of sight (LOS[2]), Non-LOS (reflected, scattered, diffracted, surface wave),
    - Frequency band of operation (VLF, HF, UHF, EHF).

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[1] We will use these terms interchangeably to cover all aspects of ECM & ECCM - sometimes lumped together under the term Electronic Protection Measures - EPM.

[2] LOS: We will use the term LOS for radio line-of-sight which includes the effects of earth's curvature and atmospheric density gradients. BLOS = Beyond LOS.

Other attributes that could be considered are active (SATCOM) and/or passive relay operation with LOS systems, antenna characteristics (omnidirectional, directional, narrow beam, adaptive beam forming), and type of ECM protection (frequency hopping, direct sequence/CDMA spreading, et cetera). All of these characteristics have EW and propagation implications. For example, synchronous data systems can be fragile and easily disrupted by electronic means. Similarly, digital speech systems are more vulnerable from an ECM viewpoint (but provide more robust message security with powerful encryption algorithms). Beyond or non-LOS HF, meteor-burst systems are difficult to jam from locations that are not within radio LOS of the victim receivers, as opposed to LOS radio systems, et cetera.

The issue of voice versus message/data communications also has significant EW implications. Voice communications are practical, robust, and easily interfaced to the user, both in source (microphone) and sink (earphone/speaker) terms. However, for many applications voice communications is slow and inefficient due to its serial nature. For example, a voice message reporting tracks for 10 seconds could be compressed into a formatted data message that is just a small fraction of a second over the same communications system. Data communications can therefore provide significantly lowered electromagnetic exposure by reducing transmission times, and also allow the implementation of more robust security measures in many instances - if suitable user interfaces are available.

Clearly, the above delineation results in many combinations, and each item (or group) has specific properties that make a certain set of EW approaches (and corresponding ECCM) effective/affordable. A large number of combinations is possible, therefore we will only consider some primary combinations from the above.

- Radio LOS systems:
  - VHF, UHF, S/EHF radio systems (& LOS HF),
  - SATCOM systems (highly specialised active relay LOS radio).

- Non-LOS radio systems:
  - Ionospheric reflection (HF),
  - Surface wave (land, maritime, rough terrain),
  - Meteor Burst.

Radio Line-Of-Sight (LOS) Systems

These systems cover a very large frequency spectrum. For such systems, the electromagnetic signals are transmitted/received between radio LOS units with appropriate antennas. As the frequency increases, radio LOS approaches optical/visual LOS. SATCOM systems are highly specialised LOS radio systems that employ an active relay, and are treated in a separate section below. From a propagation view point, there are essentially two LOS systems with an unmanned active relay. However, the characteristics of the highly specialised active relay - the satellite - provide very significant functionality and advantages at the expense of complexity and cost. The location of the orbit (synchronous, low), the frequency band, on-board processing, and antenna characteristics all are important factors as discussed below.

VHF, UHF Radio Systems (& LOS HF)

These systems operate from about 20 MHz up (upper HF, VHF, UHF, EHF), but in some cases lower frequencies can also be utilised for radio LOS communications. Diffraction/scatter effects can also provide some useful surface wave, non-LOS, coverage in rough/mountainous terrain for frequencies up to few hundred MHz. Depending upon elevation of the antennas, communication links over hundreds of Kms can be set up.

There are now, in the nineties, many frequency hopping (FH) radios that cover these bands, and many more can be anticipated in the coming decades. These systems range from slow hoppers (few hops per second) to fast hoppers (many tens of Khops per second). They are, of necessity, synchronous (all transmitters/receivers must be synchronised), and therefore require good timing and/or time distribution mechanisms. Most FH systems are based on constant dwell time on each frequency of the hop-set, but non-constant dwell times can be implemented and provide significant EW benefits. The advantages of FH as an ECCM measure for LOS, and particularly sparsely deployed systems (small number of transceivers in a radio LOS volume), is clear. However, for non-LOS systems such as HF (ionospheric reflection) and meteor burst (scattering from cold

plasma trails formed by microscopic meteor dust in upper atmosphere), an analysis of all relevant aspects (scenario/deployment density, threat sophistication, cost/complexity/risk trade-off) does not necessarily lead to the same conclusion, especially for tactical systems.

The state-of-the-art in fast scanning receivers and associated signal processing is such that speed of hopping is no longer a primary issue, even for relatively fast-hopping systems. Operating in a real environment, where there are many other electromagnetic emissions (other hoppers, fixed frequency transmitters, noise/interference sources) does, however, provide difficulties for the jammer who may be trying to follow a FH signal.

In the coming years, follower jammers, which do not merely look for energy in a frequency "bin" but also perform some form of signal/signature analysis to identify particular nets of interest, can be expected to proliferate. This technology will benefit from extensive related work for sensor systems.

Non-constant dwell time systems, where the instantaneous hopping rate is also a pseudo-random function of time (controlled by a protected key), have very effective ECM implications and can be expected to proliferate in the future. When the dwell times of the hopping signal becomes comparable to the propagation times (for example, as implemented in the US Joint Tactical Information Distribution System - JTIDS), even if the signal could be followed in frequency, the jammer must overcome complex spatial/geometrical limitations. Such systems can be expected to provide the main component of radio communications systems that offer the ultimate in ECM protection in the future.

Power levels/availability for jammers is an issue for mobile, particularly airborne, ECM platforms. However, in the coming years, the brute force "classical pure power battle" in ECM/ECCM (=EPM) can be expected to be increasingly augmented and/or replaced by efficient signal processing approaches. This will produce similar end results, without the potential danger of electromagnetic pollution effecting own communication and sensor systems.

Direction-finding (DF) or geolocation accuracies on communications signals in these bands is a function of many parameters: frequency, DF antenna aperture size, distance/signal strength with/without triangulation from separate locations, et cetera. As a general rule, DF accuracies of fractions of a degree can be attained for radio LOS fixed/slow-moving targets, particularly for higher frequencies and/or (with good triangulation baselines) from fixed locations. For DF on mobile targets from mobile platforms, accuracies around a degree can be obtained for better systems, but typical figures for realistic scenarios would be of the order of few degrees. Only some incremental improvements on these accuracies can be expected in the coming years, since physics of wave propagation and antennas precludes any revolutionary developments.

A recent important development is the availability, at low cost, of spread spectrum SHF/EHF (few GHz and up) LOS radio equipment for high capacity (2, 4, 8, ... Mbps - E1 or T1 multiples) digital LOS links with large spreading factors. These systems are based on processing gain derivable from bandwidth expansion (Shannon), and utilising extremely low powers to permit widespread utilisation without frequency clearance. Typically, a 2 Mbps duplex link for LOS distances up to 50 Km can be set up with 100 mW spread over 120 MHz at 5.7 GHz (Cylink/Airlink), with very small dish antennas.

Such systems are now becoming increasingly more affordable, due to developments in high-frequency semiconductor and hybrid circuitry production technologies, driven by large potential markets. Such systems are very recent, and are presently mostly being used as fixed links as an alternative to costly leased lines, complementing the large capacities available in fixed terrestrial/maritime photonic (fibre-optic) networks. However, they can also be readily used for quick set-up, high-capacity LPI applications. On the commercial side, the proliferation of such systems will increase, driven by the "information revolution" and the "information (super)highway" requirements of the Internet, video-on-demand, video teleconferencing, et cetera, but there will also be very significant military applications due to their LPI characteristics.

It is very interesting that the military requirement of "low probability of intercept" (LPI) communication should now be available as a part of a commercial product due to a totally different reason, that of ease of spectrum support, at costs that are orders of magnitude less than specialised military LPI systems.

SATCOM Electronic Warfare Considerations

Satellite communications (SATCOM) provides the primary means of communicating at beyond line-of-sight distances for field operations of the militaries of the western world. Recently, the technology advances in military satellite communications have benefited significantly from the technology and service push in the commercial semiconductor and telecommunications markets. By far, the most commonly used frequency bands fall in the UHF, SHF, and EHF bands, each including allocations for uplinks and downlinks.

Military uplink and downlink UHF frequency allocations are made in the range of 225 to 400 MHz. These low frequencies allow the use of small portable, and highly mobile, ground terminals. The applications include man-portable terminals, ship- board applications, and airborne installations. The users of UHF SATCOM typically require single voice circuits or low-speed data communications. The combination of low-frequency carrier transmissions and relatively low data rates have made possible the development of inexpensive ground terminals that are available commercially. With these characteristics, UHF SATCOM is best suited to tactical communications applications. However, UHF satellite communications are vulnerable to interference, both unintentional and intentional (jamming), and are also susceptible to ionospheric scintillation. Because of the broad antenna beams employed in the typical UHF SATCOM system, the terminals are easy to geolocate, and radiated signals are easily intercepted. Because of these threats to the use of UHF satellite communications, it is generally best suited for low-threat environments such as peacekeeping missions.

The frequency allocation (often called X-band) of 7.9 to 8.4 GHz uplink, and 7.25 to 7.75 GHz downlink, has been used for military communications from the earliest days of SATCOM. X-band systems are primarily used for high data rate communications services between fixed sites; and, recently, also for some transportable and mobile applications with a reasonable degree of survivability through spread-spectrum operations.

The newest band to be used for military satellite communications is in the EHF band, the use of which will proliferate in the coming decades. The uplink allocations are 43.5 to 45.5 GHz, and the downlink band is 20.2 to 21.2 GHz. These operating high frequencies allow relatively small, high-gain antennas to be implemented. These high-gain antennas can then be used to support high data rate communications, or be traded off to make very compact terminal implementations.

Commensurate with the increase in antenna gain is a reduction in antenna beamwidth. These smaller beamwidths can place a burden of improved pointing accuracy on the terminal, but they also reduce the opportunities for downlink jamming in the antenna sidelobes and for interception of signals. Additionally, the large bandwidth available in this band has been exploited to produce highly survivable spread-spectrum systems. These desirable survivability features of the band must be weighed against the high attenuation of signals propagating through rain. Satellite systems in this band can also potentially implement a great deal of on-board signal processing to improve survivability and enhance communications flexibility for mobile and highly transportable users. There are additional frequency allocations in the EHF band for satellite systems around 30 GHz. There is also a great deal of interest in the commercial 30 GHz band for emerging high data rate consumer communications services.

As a measure to improve survivability and reduce costs, by reducing the reliance on ground stations outside national territory, intersatellite communications links can be implemented, as have already been implemented by some nations. The use of such links can be expected to proliferate. There are allocations for intersatellite links at K-band, V-band, and in the optical infra-red frequencies. Since the atmosphere is nearly opaque at several frequencies near 60 GHz (because of oxygen absorption), V-band crosslinks cannot be intercepted or jammed effectively by earthbound adversaries. Optical crosslinks make use of highly directional antennas (e.g., telescopes) to reduce the possibility of jamming or interception.

Commercial satellite communication is expanding rapidly, as a result of world-wide deregulation of the telecommunications industry. This, along with revolutionary technology developments, is spurring massive commercial development of satellite communications systems. Commercial SATCOM services are increasingly being used for military communications needs because of the

increasing demand for communications capacity that cannot be met with military systems, the need for unique commercial services, and the desire to reduce costs. This trend can be expected to accelerate.

Means of Service Denial

A broad range of techniques are available to combatants in a hostility to attempt to deny satellite communications to each other. This section will describe this range of techniques available to conduct electronic warfare on satellite communications systems. No explicit distinction will be made about applicability of these methods to either NATO or to its potential adversaries. Generally, these techniques could be effective for both sides in a confrontation. The primary issue is the level of resources available to either side.

Since the NATO Nations are among the most technically sophisticated in the world, all of these techniques could be available to NATO, if so desired. With the collapse of the Warsaw Pact, the threat of a broad conflict between two forces with the highest levels of technical sophistication is not currently considered likely.

The most commonly considered method of denying communications is through the use of jamming. However, with satellite systems, a distinction must be made between uplink and downlink jamming. A high-power broadband noise or tone signal is radiated into the operating band to degrade the performance of satellite communications modems, effectively disrupting communications. In general, the approach taken to mitigate a jamming attack is to make use of spread-spectrum communications. In addition to the other features mentioned below, ensuring that there is adequate transmission power for the protected communications links is crucial.

An attack on the satellite uplink receiver constitutes a system-wide attack, as it is a single node through which all communications traffic must pass and the satellite position is usually well known. Frequently, satellite antennas cover large areas on the earth, reducing constraints on siting of jamming installations. Jamming equipment suitable for uplink jamming can be installed on a variety of different platforms, ranging from fixed installations to land-transportable and ship-based platforms.

Space-based jammers have also been proposed as a means of reducing the propagation losses experienced by earthbound jammers; related developments can be anticipated in the coming decades.

Downlink jamming, in contrast, generally does not constitute a system-wide attack strategy. Because of the high-transmission frequencies used in satellite communications systems, a jammer must have a line-of-sight to the receiver to be disrupted. This means that the jammer must be reasonably close to the station to be attacked; and stations are frequently separated by large distances, making a simultaneous attack on more than one station unlikely. Short-range attacks allow small transmitters to potentially be effective at disrupting communications. Since satellite earth-stations frequently have narrow antenna beamwidths, and the antennas are usually pointed up to the sky; jamming attack would most likely come through an antenna sidelobe, reducing the received jammer power level. In addition to transportable land and ship-borne jammer platforms, airborne jammers and small covertly placed jammers could be effective downlink jammers. Space-based jammers have also been proposed for system-wide downlink attacks.

To the extent that they are employed by military users, commercial satellite communications systems are particularly vulnerable to jamming attack. In general, the communications modems do not include anti-jam waveforms, antenna sidelobe control may not be a high design priority, and satellite transponders usually do not include hard-limiting amplifiers that limit the ability of a jammer from robbing downlink power.

Even military spread-spectrum systems may be vulnerable to specialised jamming attacks that seek to circumvent the anti-jamming features of the system. Generally, these specialised attacks must take advantage of detailed knowledge of the design of a communications system and, hence, are possible only for a sophisticated attacker. An attack may seek to take advantage of signal leakage in the receiver, spurious signals in downconverter chains, and receiver non-linearities to inject signals in the de-spread portion of the receiver, effectively defeating the anti-jam communications features.

Another specialised attack strategy for frequency hopped systems is the frequency follower jammer. The total propagation time (user to jammer to user), plus the processing time, must be less than some significant portion of the communications system hop duration. Finally, by means of a

repeater jammer and other means, it is possible to attack the timing synchronisation mechanisms in the spread-spectrum receiver. A very high degree of time synchronisation is especially important for direct-sequence spread-spectrum systems. Other specific system design features may unwittingly present vulnerabilities.

Another approach available to deny communications is to explode a nuclear weapon in the upper levels of the atmosphere, or just outside the atmosphere, which can disrupt a range of SATCOM/radio communications. There are three primary phenomena associated with such a detonation. First, the blast fireball produces a significant increase in the background thermal noise and causes a marked increase in RF energy absorption. These are short-time, localised effects. As a result of interactions with the upper atmosphere, a nuclear detonation also produces a large electromagnetic pulse. This pulse would be transmitted over a broad area, and could potentially burn out the receivers of unprotected radio systems and be very disruptive to many electronic systems in general. Finally, a nuclear blast produces a large quantity of charged particles in the upper atmosphere. Over time these particles form striations in the upper atmosphere causing multipath propagation that significantly degrades the performance of many satellite communications systems (also HF and meteor-burst systems). This risk is normally mitigated through the use of communications waveforms designed to operate in a multipath environment, using multiple systems appropriately networked. Research and development in these areas can be expected to continue at an accelerated pace.

Satellite communications can also be denied by means of a direct attack on the physical plant of the communications system. Fixed assets, such as large fixed-ground terminals and satellite control centres, are usually located in rear areas, well away from combat zones. However, their location would be expected to be known to an adversary and could be targeted by aerial bombardment, missile attack, or special operations units. Fixed sites may also be vulnerable to terrorist attack. Mobile ground facilities are inherently more survivable because of difficulty in locating the asset for targeting.

A direct attack on a space segment is technically more demanding, but would have much more far-reaching consequences. Attacks on satellites in geosynchronous orbits would be extremely difficult for all but the most technically capable of nations. Spacecraft in lower orbits are more vulnerable, but an attack would remain a daunting technical challenge. The most feasible attack on a geosynchronous orbit spacecraft is the launch of a nuclear weapon to the orbit location of the desired target. For spacecraft in low-earth orbit, conventional explosive devices could also be effective. Other attack mechanisms that have been proposed include: space-based kinetic energy weapons, directed-energy weapons (such as lasers or neutral particle beams) that could be used to blind sensors or damage the spacecraft, or aerosol spray devices that could blind sensors that maintain platform stability.

Another possibility is extremely high-power signals radiated into the user's communications bands, perhaps for only a short period, towards a receiver, in the attempt to damage or destroy delicate electronics. Such "directed-energy" type of attacks, would clearly be applicable to the whole range of electronics equipment, but satellite systems are particularly vulnerable since they provide high-value nodal connectivity. Commercial systems are not, at present, typically designed to survive such extreme RF overloads, but may be in the future.

An adversary may attempt to enter the normal operation of a communication system and, by introducing appropriate command signals, disrupt the operation of the system; this is spoofing. For satellite communications systems, the two primary targets are the controllers of demand-assigned communications and the command sub-system of the spacecraft. The range of attack strategies is quite broad. Generally, encryption of command links and control orderwires is effective in reducing the risk of such an attack. Even if the controller is only "spoofed" with messages that ultimately fail an authentication check, such an attack may be effective in degrading access for the intended users of the system. Such spoofing messages could be generated by monitoring communications and repeating the messages of valid users. Spread-spectrum systems using high-quality, time varying TRANSEC algorithms are effective in mitigating this sort of intrusion, and such protection measures can be expected to proliferate.

To the extent that commercial satellite communications systems are used by military forces, it is possible to deny services by non-technical means. Both INTELSAT and

INMARSAT, the large multinational consortia that provide international satellite communications services, have restricted the use of their respective systems to peaceful purposes only. EUTELSAT has similar language in its charter. These restrictions have been interpreted to mean that military operations sanctioned by the United Nations can use their services. Thus it is conceivable that, in the future, service could be denied by political action within the United Nations and/or multilateral national initiatives.

There are also several commercial satellite systems that are privately owned (as contrasted with the quasi-governmental organisations mentioned in the last paragraph) providing international satellite communications services. There will be a significant increase in the number of privately owned international systems as the new mobile service systems and the new Ka-band fixed service systems are brought into service in the next few years. Since these systems are fully commercial, it may be possible to deny services to an adversary by paying a fee to the service provider.

Means of Exploitation

A variety of techniques are also available for conducting electronic warfare that do not seek to attack the SATCOM system, but rather to exploit an opponent's system for military advantage. Exploitation seeks to determine information about an adversary and its military operations by different levels of analysis of satellite communications signals. These threats are passive and hence can be practised and implemented before the onset of hostilities.

Counter-Counter Measures

The developments in counter-counter measures areas are primarily spurred by the exponential growth in capabilities of digital processing. Military space programs will, for first time, be able to take advantage of commercially developed space technology. Demodulation on the spacecraft is more effective than the conventional transponder hard limiting, but it increases the payload and complexity of an already complex satellite.

Another technology that is available for use in satellite communications systems is antenna beam-forming. In concert with spread-spectrum signal processing, this technique can greatly improve the performance of a satellite communications system in case of a jamming attack. These anti-jam antenna systems are usually thought of as being on the spacecraft to protect against the threat of an uplink jamming attack. Though certainly feasible for use to defend against a downlink attack, nulling antennas are not often considered in such cases because of the cost of such a system versus the limited geographic extent of downlink attacks. A single uplink jammer can disrupt communications over a wide geographic area, while one downlink jammer would be required for each receiving station. These anti-jam antenna systems are composed of several important sub-systems: the radiating structure (the physical antenna), a beam-forming network, the control processor, and the control algorithm. Each have important present technology implementations and can be expected to advance in the coming years.

In order to be effective in a broad range of operational scenarios and to counter the effects of different jamming strategies, anti-jam antennas must be able to adapt to changes in user or jammer locations and jammer power levels by suitably determining the beam-forming weights to produce an antenna gain profile that reduces the received jamming power while providing sufficient gain for the desired users of the system. The rapid development of microprocessor technology is making impressive gains in nulling control processors possible. By making measurements of the jamming signals in each element of the antenna, it is possible to determine beam-forming weights that produce the desired antenna gain pattern. In early developments, these measurements were relayed from the spacecraft to the ground for processing. With the new computer technologies, it is possible to place the control processor in the communications payload. This will increase the speed of response of the control algorithms and improve their accuracy. Another key benefit of the improvements in processor technology is the increased processing capacity to handle more complex control algorithms. Related developments can be expected to accelerate in the coming years.

Small Terminals

There is a great deal of interest, in both the military and commercial sectors, in the development of smaller and more transportable terminal equipment. This is typified by the

development of hand-held telephones (terminals) for the new personal communications satellite systems, and by the man-portable UHF and EHF terminals for military applications.

In addition to the revolution in digital processing technology, the push for small terminals is driving the development of smaller and more efficient transmitters, denser packaging for radio frequency components, and more efficient batteries.

Also of great interest for mobile applications are the development of conformal antenna arrays. This antenna technology, which is advancing rapidly, employs electronic beam-steering of tiny array elements and, thus, does not interfere with the aerodynamic properties of the host platform. These technologies will proliferate.

Non-LOS Radio Systems

Beyond-LOS (BLOS) or non-LOS (NLOS)[3] systems encompass various scatter, reflection, diffraction, surface-wave systems which permit the transmission of sufficient electromagnetic radiation for communicating information between users that do not have radio LOS between them. Non-LOS could be due to distance and curvature of earth or simply blocking by natural/man-made obstacles. No technological breakthrough in BLOS propagation modes is anticipated; therefore, only incremental increases in available capacities will be available.

A recent well-documented case is the difficulty of communication between relatively close UN teams in the mountainous regions of former Yugoslavia, and the resulting initial proliferation of INMARSAT satellite terminals. In such terrain there can be useful diffracted signal levels well below conventional radio LOS positions, for transmissions up to some hundreds of MHz. It car be shown that LOS obstruction by sharp peaks ("sharp" with respect to the wavelength), can provide significant "obstacle gains," resulting in good signal levels in wave-shielded areas. Such signals are particularly usable for asynchronous packet radio data communications where the inherent ARQ (automatic repeat request) process of the protocols can introduce robustness. The most important BLOS medium is the HF band (2 - 30 MHz), in which ionospheric reflection mechanisms provide useful signals for distances up to many thousands of Kms (essentially all over the earth). The popular short-wave broadcast radio stations operate in this band, and provide world-wide coverage.

Direction-finding (or geolocation) uncertainties for BLOS communications signals are inherently much higher than for LOS systems, due to the random perturbations induced by the reflection mechanisms. DF accuracies are again a function of many parameters; frequency, DF antenna aperture size, distance/signal strength with/without triangulation from separate locations, et cetera. For non-LOS systems, these are also compounded by the non-linear, random/time-varying parameters of the reflection mechanisms. If the DF facility is restricted to a BLOS location with respect to the transmitter, accuracies less than few degrees are difficult to obtain for even slow-moving targets. Such accuracies will convert to many tens of ms of uncertainty as to the location of transmission (in blue-water naval scenarios this may not be a problem, as the deployment densities are very sparse).

Only some incremental improvements, derived from more accurate modelling of the reflection phenomena and signal processing, can be expected in the coming years, since physics of wave propagation and antennas precludes any revolutionary developments. An important development that can be anticipated is further work in, and resulting better understanding of, the chaotic/fractal effects inherent in ionospheric (and possibly other) reflection mechanisms with large non-linearities. These will result in absolute limits to our ability to observe/measure certain effects (as has turned out to be the case in meteorology - succinctly described by the term "butterfly effect"), i.e., it is unrealistic to assume progressively increasing accuracy of passive ionospheric prediction models. As a result, robust techniques that require limited characterisation of difficult channel conditions will find increasing applications. For example, link-level ARQ protocols for data communications will allow error-free communications over a very wide range of channel conditions, by automatically trading off message delivery duration with channel conditions. Such techniques will be further refined and proliferated.

[3] We will use these terms interchangeably. However, in some analysis NLOS is used for short range blocked links and BLOS for long range beyond horizon instances.

Ionospheric Reflection (HF)

Until the advent of communications satellites, from the late sixties onward, the only practical means of unrelayed long-distance communications was HF communications. This mode of communications utilises the reflection of signals from the various cold plasma formations (ionospheric layers) induced by solar radiation. The phenomena that cause these ionisations are complex and highly time-variable (diurnal, seasonal, solar cycle). As a result, the "science" of HF communications, and the associated electronic warfare techniques, had a significant component of "art" until the eighties. Developments in the last decade have significantly reduced this component of HF communications by automating many of the required functions. Ionospheric reflection systems will continue to be used as non-LOS, low-capacity systems, and as back-up to vulnerable satellite systems.

The HF frequency band is, by far, the most densely occupied band of the radio spectrum. Many tens of millions of HF transmitters world-wide utilise this band for communications, with output powers from few watts to hundreds of kilowatts. It is possible to estimate that gigawatts of electromagnetic energy is radiated world-wide in the 28 MHz band, at any given moment. Because significant portions of this energy can be refracted/reflected back to the earth - depending upon the frequencies, ionospheric conditions, et cetera - the electromagnetic pollution effects are considerable. This situation is not expected to improve in the coming years. In spite of these, HF communications is still the most cost-effective means of voice and low-rate data (few kilobits/sec) BLOS radio communications; and it will continue to be so, since the equipment required is simple/low cost. While the medium is complex, as propagation relies on semi-predictable natural phenomena, this complexity/unpredictability also makes the job of the adversary (jammer/interceptor) inherently difficult, a factor that is sometimes neglected.

The developments in the area of spread-spectrum (direct-sequence and/or frequency hopping) ALE/ALM[4] signal processing (including adaptive array antennas) and protocols have now given HF communications much better performance. These also have significant ECM/ECCM implications.

The developments in these areas will continue, and more effort in effectively combining these capabilities can be anticipated in the study time-frame. There is on-going work in wide-band, direct-sequence HF systems, in which the objective is to utilise bandwidths much larger than the present few KHz, by adaptive equalisation. Such systems are aiming to provide effective non-LOS stealth communication systems in the future. The technological push for the extension of the data rates within the present ≈ 3 KHz bandwidth standards for HF channels will continue. Practical 4.8 Kbps modems (≈ 2 bits/Hz) can be expected soon, and work on 9.6 Kbps modems (approaching 4 bits/Hz) will continue and will provide results within this decade. The complexities of international spectrum management in the HF band, rather than technology, will most likely restrict the potential for wider bandwidth systems. However, wartime modes in HF equipment may over-ride such limitations.

Frequency hopping HF systems are now becoming available, and continued enhancements can be expected. For beyond LOS links, the speed of hopping is a less significant factor, and even hop rates of few tens per second can provide sufficient protection. However, the restrictions and the complexities that may be imposed, particularly on tactical users, by FH will need to be carefully analysed. The advantages of FH are clear for LOS radio systems, but they do not necessarily carry over directly to BLOS radio systems - particularly in a densely polluted spectral environment such as the HF band. Developments in fast ALE/ALM will also provide substantial levels of protection.

Surface Wave

Non-LOS surface-wave communications are significant; both for scenarios over large distances, particularly over sea paths; and for relatively short-distance communications in rough/mountainous terrain. At low frequencies, substantial propagation can be obtained with surface waves; the lower the frequency, the longer the distance. For maritime communications, much higher distances are possible because of the higher conductivity of sea water. For frequencies of the order of tens of KHz and with large power levels (antenna coupling efficiency is a big issue), in principal, all of the earth could be covered, albeit for very low data rates. At few MHz and

[4] ALE: Automatic Link Establishment
ALM: Automatic Link Maintenance

below, distances up to many hundreds of Kms are possible over average sea water, with few kW power and practical antennas. In mountainous terrain, the diffraction effects can produce significant signal levels in areas that would normally be in radio shadow. These effects are practically usable up to few hundred MHz, but are much more significant for frequencies from about 20 MHz to 100 MHz.

For non-BLOS communications in such mountainous terrain, a new generation of adaptively equalised single-tone modems allows the combined diversity use of HF sky wave (ionospheric reflection) and surface wave, providing much improved performance. With normal frequency shift or tone-keyed signalling, each of the two signals would normally prevent the other from being demodulated. Developments in such adaptively equalised modems will continue and will provide even more improved performance. These developments will also enhance communications capabilities for polar areas, where auroral effects are significant.

Surface-wave signals are somewhat more difficult to attack with ECM, because of the normally higher and more constant signal levels at receivers, and the geometric restrictions on the electronic attacker. HF systems that utilise the very effective diversity provided by sky and surface waves, through the implementation of adaptive single-tone modems, will become increasingly more available . This new class of modems utilise multipath, even with very large delay differentials, as diversity. Such modems will also provide very effective EW protection, as the adversary will be forced to implement surface-wave and sky-wave jamming.

Meteor Burst

Meteor-burst systems are relatively novel systems that use the cold plasma trails formed by the many microscopic cosmic dust particles that enter the earth's atmosphere. Due to their unique characteristics, their implementation is increasing and is expected to continue. The density of meteor dust particles has diurnal, seasonal, yearly and sunspot cycle variations. However, even though the actual link is available at random times and for random periods, they can provide very effective stealth communications for near real-time data and voice communications. These systems have the unique characteristics that the transmitter and receiver essentially wait for the occurrence of a specifically aligned random trail (tangent to the oblate spheroid with the transmitter and receiver as foci) for the establishment of link. This results in reception footprints around the receiver beyond which signal level falls of rapidly. As result, the jammer must either be LOS to the receiver or very close to the transmitter, so as to ensure that its energy is reflected off the same meteor trails. Both of these are significant restrictions that make jamming of MB systems highly unlikely. This unique characteristic results in what can be termed "geometric stealth". Instantaneous bandwidths (or equivalently data rates) are increasing as a result of improved understanding of the relevant mechanisms.

Conclusions

Communicating information (voice, message/data, graphics/images) is, and will remain, a most vital aspect of crises/conflict management, peacekeeping and warfare. Terrestrial/fixed communications is going through a revolution generated by photonic/fibre-optic and signal processing technologies, so that capacity between fixed users is no longer an issue. Fixed infrastructure and related elements/headquarters will, in the coming years, be able to have access to essentially limitless communications capacity. The associated information systems (IS) support will grow based on these large capacities. However, there is no technological breakthrough anticipated for increased communications capacities to the mobile/tactical user, only small incremental increases can be expected; therefore, such users must use capacity much more efficiently. Wireless or radio communication, will be the essential element of all mobile operations, tactical and otherwise, and a significant component of higher level command and control requirements. As more efficient communication techniques are developed, more sophisticated ECM and ECCM will also continue to be developed in parallel. Wireless or radio communications will probably be more vulnerable to adverse action than terrestrial fixed communications. Fixed-radio communication systems will also be more vulnerable than mobile systems - for obvious reasons.

The most generic and powerful means to reduce risk of disruption of communication systems is media diversity or proliferation of available

media through open networking. For data/message systems, the use of packetization so that routing over diverse media/networks can be accomplished, is an additional factor. It will also be possible to "packetize" real-time speech with the proliferation of "fast-packet" or ATM[5] techniques. Such highly interconnected networks and associated protocols/standards, like those used for the current Internet, combined with digital wireless systems such as GSM, will provide the basis for much of future communications. ATM will provide the technology for larger capacities.

As communication systems become increasingly networked and multifunctional, management of these systems will become complex and highly automated. The disruption of such systems by malicious software (viruses, worms, et cetera) will become an increasingly significant electronic threat, in some cases possibly more so than classical threats posed by jamming, spoofing, and others.

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[5] ATM: Asynchronous Transfer Mode

References

This report is unclassified to permit wide distribution and exposure. Unclassified references in the area of communications EW/ECM/ECCM/EPM may be found in many sources and are not given for brevity. There are only a few periodicals that cover specifically EW, **The Journal of Electronic Defense** (http://www.jdefense.com) is an excellent unclassified up-to-date source for developments in the area of EW (it covers all aspects of electronic warfare/defence including sensors and informatics). Some technical publications, e.g., IEEE Society Transactions/periodicals (http://www.ieee.org) and also those of the IEE also occasionally publish articles in the area of communications EW. To assist the reader with access to classified sources we give below some classified references that may be of interest. The first two references below are classified volumes of conference proceedings and include a number of relevant papers. Most of the papers below also contain useful classified references.

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ANNEX 2: SYNTHETIC ENVIRONMENTS

The rapidly evolving concept, referred to here as "Synthetic Environments," and elsewhere under such titles as "Advanced Distributed Simulation," will help all those people closely involved with any particular issue, to understand the problem, define the military need, explore alternatives, and make decisions.

The contribution of simulation to operational effectiveness in defence is not new. Simulation has been employed in aviation for over 35 years, in many different ways. Indeed, it has been said that "everything is simulation except actual combat".

Simulations are currently divided into three broad classes: constructive simulation, virtual simulation, and live simulation. Constructive simulations involve simulated people using simulated equipment; an example is the "TAC Thunder" analysis model. Virtual simulations involve real people using simulated equipment; an example is the pilot-in-the-loop flight simulator used in engineering design or in training. Live simulations involve real people using real equipment, such as the "Red Flag" style of exercise (real bombs and bullets may or may not be used).

Up to now, simulations have been largely stand-alone. What is new is that major advances in the technologies of computing and communications, along with reductions in cost, now enable the defence community to put together integrated collections of simulations. These are what constitute "Synthetic Environments," with the emphasis on the aspect of integration. Advanced computer graphics will also enable all "stakeholders" to visualise what the simulations are doing, so that judgements and decisions can be based on a better understanding of the problem and of the possible solutions.

Significant technological developments are required in:

- The creation and use of common models,
- Configuration management and control,
- Validation,
- Data base generation and an adequate level of fidelity,
- Multilevel security,
- Variable resolution.

Current Status

Work on Synthetic Environments is already under way in various government and industry programmes in several nations. Many Defence establishments in NATO countries are experimenting with Synthetic Environments.

A 1992 US Defense Science Board report on the 'Impact of Advanced Distributed Simulation on Readiness, Training and Prototyping' has been a major stimulus. Distributed simulation, one key to creating cost-effective Synthetic Environments, is an emerging and rapidly evolving technology. For example, STRICOM, the Advanced Research Projects Agency (ARPA), and other organisations in the United States are developing distributed simulation protocols.

The application of integrated simulations to developing system requirements and defining system needs is currently under way in the US, France, and the UK. Advanced distributed simulation is in use today. An example is the recent (November 94) Exercise "Atlantic Resolve" and its associated Synthetic Theatre of War - Europe (STOW-E) demonstration.

There are several developments under way in the US which rely heavily on synthetic environments. An example is the Joint Distributed Simulation Joint Test and Evaluation, which is investigating the utility of distributed simulation technology for both developmental and operational testing. Three major test activities are planned: a systems integration test, involving an advanced missile system; an end-to-end theatre battle arena systems test; and an electronic warfare system test. The objective of these test activities is to evaluate distributed simulation technology, rather than to test the systems involved in the experiments.

Distributed Interactive Simulation (DIS) standards exist, and are in use today. Distributed Simulation technology is still evolving, however, with many significant developments, such as the High-Level Architecture, to come. It will continue to improve and evolve over the next 10 - 20 years, aided by growth in computer processing power, massive parallel computation, and other innovations.

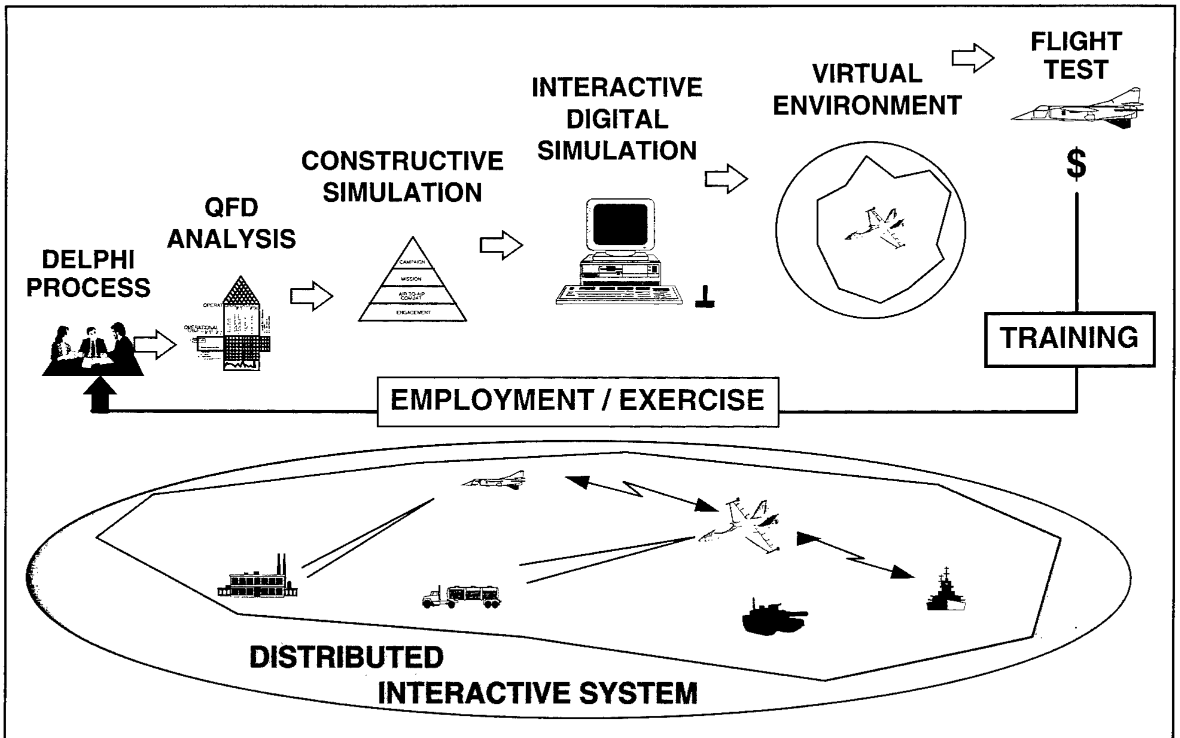

Figure 1: Modelling, Simulation and Analysis Process

Technical Issues

Near-term actions to exploit emerging technologies are needed in the following areas:

- Architectures and standards for distributed simulation, a foundation for Synthetic Environments;
- Better models of human performance and behaviour, with allowances for training level, fear, fatigue, et cetera;
- Validation methods for the outcome and results of large-scale simulations[1];
- Synthetic Environments must be easy to use, secure, reliable, and affordable.

Risk factors that need to be recognised include the following:

- Software development and validation methods must be improved. Synthetic Environments are large-scale, software-intensive systems, requiring validated models; they are, therefore, heavily dependent on software technology;
- Data is at the heart of all simulation and modelling. The definition of common data base standards, and the creation of validated data bases of the environment, and of equipment, are crucial steps;
- Other technical challenges include:
    - Scalability,
    - Fidelity (particularly higher resolution entities),
    - Integration of live, virtual, and constructive entities,
    - Threat emulation, using distributed signature models,
    - Terrain and environmental representation; data rates and latency,
    - RF Data links for virtual threat injection; verification,
    - Validation,
    - Accreditation;
- A key feature of Synthetic Environments is that they enable the human element to be included during all stages of specification, development, and deployment of a military system. However, metrics to evaluate mission effectiveness, system effectiveness, human

[1] See for example *"VV&A of Synthetic Environments: proposed Definitions"*, Position Paper 96-14-164, by R.J.R. Miller and P allen, 14th DIS Workshop, Orlando, March 1996.

performance, and training effectiveness are currently inadequate. There are major concerns about the ability to induce stress and fear in human combatants participating in Synthetic Environments;

- The vulnerability of any information technology system to overt and covert attack will remain a risk factor until system security methods are greatly improved.

Simulation is a continuum consisting of a series of models of ever-increasing breadth. Beginning initially as a delphi process, system requirements are subjected to ever-increasing levels of analysis - to determine both their effectiveness at achieving system performance and their linkage to higher objectives. At some point in the process, we must begin quantitative assessment of the effectiveness of our system and its principal attributes. To do this, we must first agree on a hierarchy of models that all players must then utilise to make assessments.

In addition, we define the performance criteria (MOP, MOE, MOO) that will be utilised to evaluate the outcomes. Once this architecture has been constructed and agreed, then we can move through a modelling and simulation process of ever-increasing fidelity and complexity, such as shown in Figure 1.

Ultimately, the modelled system can be inserted into an even broader architecture of complementary systems. Given the complexity that such a system-of-systems entails, a single simulation encompassing every aspect of play for all systems would be of such complexity as to make the process unachievable. The solution of lowering player fidelity risks over-simplification to the point of invalidating the result. Therefore, we design a distributed simulation in which each component is played by the most knowledgeable players in separate, but interactive and compatible, environments. Linking these environments with proper protocols allows an extremely complex simulation (i.e., a joint warfare campaign) to be accomplished within the capabilities of our facilities. In addition, human interaction can be more closely modelled, as we can allow a larger portion of the simulation to be "human-in-the-loop".

ANNEX 3: PROPAGATION, SCATTERING, AND MODELLING

Potential Improvements in Environmental Sensing

Many important factors from the environment can affect the performances of RSTA systems in operation. These effects have to be taken into account carefully and, if possible, predicted, in order to obtain the best system performances. Prediction techniques from models, as well as estimation techniques via direct sensing and remote sensing, are now available to achieve this goal, leading to a new generation of more flexible and efficient systems.

Electro-Optical Propagation

"Electro-Optical propagation" comprises one band for accomplishing RSTA, i.e., UV (0.2 μm) to IR (14 μm), and its importance cannot be over-emphasised. This importance derives from the fact that numerous guided weapons rely on being able to observe targets in this band, and there are also a number of sensors for reconnaissance and surveillance which use the band. In fact, no other topic is as important to RSTA as the propagation of energy in this band. For the purposes of this discussion, the term "Electro-Optical RSTA" will be used as a short notation for wave propagation in this wavelength band.

The high emphasis on smart weapons with electro-optical (EO) sensors is putting increasing demands on the assessment of atmospheric EO effects. In comparison to refractivity assessment, where the spatial scales of interest are in the tens to hundreds of Km, for EO applications the scales of interest are usually an order of magnitude less. Also, atmospheric variability can be much larger for EO systems than for those dependent on radio refractivity. For example, the extinction of a cloud may be many hundreds of dB above clear conditions, which poses a particularly challenging problem for real-time prediction of EO propagation conditions through broken clouds.

There are four atmospheric parameters which affect EO propagation: molecular extinction, turbulence, refraction, and extinction (i.e., absorption and scattering) by aerosols.

Molecular extinction by the various gases found in the atmosphere is well understood for most EO systems applications. Molecular extinction can be quite severe in certain spectral regions, which EO systems either avoid or sometimes exploit. Atmospheric turbulence may degrade the coherence of a high-resolution image or change the precise position of a laser beam, and thereby limit the performance of a system. Refraction may bend the propagation of optical energy and may, for example, shorten or extend the optical horizon. In the following, only the question of sensing aerosol extinction is addressed, since aerosol extinction is by far the most significant limitation for EO sensors and it is also the most difficult to measure and predict.

While there are some deficiencies in our understanding and our models for propagation in the UV to IR band, they are probably not of the "show-stopper" variety. That is, for the most part, they represent unusual conditions or situations which occur rather infrequently. In addition, there are a number of codes in existence today that describe propagation in this band. For example, LOWTRAN, MODTRAN, and HITRAN are codes developed by what is now known as the Air Force Phillips Laboratory in the US, and they apply to low, moderate, and high-resolution transmission predictions. The US Army Research Laboratory (Battlefield Environment Group) developed and maintains a code called EOSAEL for propagation in a battlefield environment. There are even codes to predict target signatures; one of these, NITRATAM, which deals with IR radiation from aircraft, was developed by a NATO study group. FLIR 92 is an example of a code that predicts sensor range performance.

All of these codes appear to be maintained and updated as new data becomes available. However, the greatest shortcoming that impacts these codes is the input parameters characterising the environment. Clearly, these are absolutely critical to the accuracy of the codes, and yet, in many instances, there is no way to obtain the parameters because of the adverse nature of the surroundings. Thus it would appear that the present state of affairs is that there are very robust prediction algorithms available, but there is a very limited

capability in the area of providing the needed inputs to these codes.

It is doubtful that there will be revolutionary breakthrough to provide the along-path medium parameters that are required by the codes, which will then provide guidance to a pilot as to the probability of success of one of his missiles. So, how then might such information be obtained in a battlefield situation? Clearly, there are a number of solutions that go a long way to accomplishing this purpose. By in large, all of these solutions are of an evolutionary nature. For example, it may be that sensors in the millimetre-wavelength band might give estimates of the along-path medium characteristics that would be useful for UV to IR band sensors. It should be noted that this is an area where civilian technology will have no impact, because there will be little to no research supported by civilian technology needs. As evidence of this, one only has to look at the transfer of passive night vision device technology to the civilian market. While there are some sales to law enforcement agencies and other specialised organisations, it is doubtful that such sales will support further research and development by the companies who make these devices. If improvements are desired in Electro-Optical RSTA, they are going to have to be funded by military directed research. In view of the atmospheric conditions in NATO countries, and the heavy reliance upon such systems, it would seem that this is one area that should continue to evolve toward increased predictability.

ElectroMagnetic Propagation

ElectroMagnetic Propagation effects often significantly affect the performances of RSTA operational systems, particularly those relying on radars and radio communications. These propagation effects have to be taken into account carefully, and if possible, predicted, in order to obtain the best system performance. Direct-sensing and remote-sensing techniques are now available to achieve this goal, leading to a new generation of more flexible and efficient systems.

Sensing of radio refractivity has historically been accomplished with direct-sensing techniques such as radiosondes. They are still the most frequently used direct-sensing technique for obtaining radio refractivity profiles. The advantage of radiosondes is their universal availability; their disadvantages are the non-vertical flight path of the balloon (or parachute for drop-zones), the time it takes to measure one profile, and the radio emissions necessary to relay the data to the receiving station. Both the non-vertical sampling path and the temporal changes during the measurement do not necessarily provide an accurate vertical profile. This must be considered when comparing true vertical, instantaneous profile measurements (e.g., lidar profilers) with radiosonde data.

Unlike radiosondes that provide temperature and humidity data from which refractivity is calculated, microwave refractometers measure radio refractivity directly. Microwave refractometers are considered the most accurate sensor for radio refractivity and usually have very rapid response times. Their disadvantages are relatively high cost and weight, in addition to the non-vertical flight path, and the time to measure a vertical profile.

Remote-sensing, satellite-sensing, radio propagation, or data-assimilation techniques can be used. One remote-sensing technique of high potential for operational assessment involves monitoring known radio transmitters. Especially in coastal regions, one usually finds an abundance of land-based transmitters which can be passively monitored off-shore. Signal levels of known emitters may be related to refractivity structure.

Ship-board radars may sense returns from the sea surface, and in the presence of ducting, these sea-surface clutter returns may be modified by atmospheric refractivity. An example is clutter rings that are caused by multiple bounces of a radar signal between an elevated refractive layer (responsible for a surface-based duct) and the sea surface. In that case, the height of the reflecting layer (height of the duct) can be calculated from the geometry involved. Much more difficult is separation of the combined effects of sea-clutter enhancement and evaporation ducting. The ocean-surface properties affecting clutter (such as wind speed and direction) are not necessarily related to evaporation duct parameters, and both effects are measured simultaneously. No reliable technique has been proposed to separate the two effects, which is necessary before ship-board radars may be used as evaporation duct sensors.

Another technique involves radio signals emitted from satellites in an attempt to relate refractive bending to refractivity structure. The bending effect is only significant within a few degrees of the horizon and, therefore, primarily of interest

over oceans, where unobstructed horizons are found. Refractivity structure may be deduced from a shift in the observed interference pattern when compared to standard conditions. This technique is presently being pursued using Global Positioning System (GPS) signals. Data-assimilation techniques deserve special attention in the sense that meteorological mesoscale models are presently available with 20 Km horizontal grid spacing and 30 levels total in the vertical; there are ten grid points in the first 500 m, with a 25 m spacing near the surface and 75 m near 500 m. Newer models being tested have a 10 Km grid spacing and a total of 36 levels in the vertical. A data-assimilation system comprising such models and utilising remotely and directly sensed refractivity data is undoubtedly the right approach to describe and forecast refractivity conditions.

Surface Clutter

Surface clutter is also an inseparable component that nearly all RSTA systems must deal with. In one particular instance (such as target acquisition) it may be highly undesirable, while there are other instances where it may contain a particularly useful signature (such as in the surveillance of terrain).

When considering the state-of-the-art relative to surface clutter, there are two criteria that must be addressed: do we understand surface clutter; and can we predict its characteristics based on rather primitive knowledge of the environment? Understanding is absolutely essential to the development of any clutter-suppression technique; conversely, it is fundamental to assessing the meaning of remote sensing data. Predictability, on the other hand, promises almost unlimited versatility, in the sense that radars can be "tuned" to the mission to enhance their performance.

There are two relatively recent scientific/engineering events that have had a significant impact on our understanding of, and the predictability of, surface clutter. The first of these is the proliferation of civilian spaceborne, synthetic aperture radars having high-resolution and multiple-polarisation capability. The world-wide data base generated by these systems is almost beyond comprehension in the range of surfaces encountered. This data base gives an engineer the ability to see exactly how different surfaces respond, and these results can be incorporated into an empirical data base that is invaluable. There is a drawback; the civilian spaceborne systems cover relatively few frequencies and viewing angles. But this is where modelling comes in, particularly numerical electromagnetic scatter modelling; that is, the models can be "calibrated" using the frequencies and viewing angles of the present SARs, and then the model can be used to predict what will happen outside these limits.

The key to this approach is the availability of robust scattering models. For a number of years, a great deal of analytical work was performed to develop as simple a model as possible. More recently, researchers have turned their attention to bringing the power of computers to bear on this problem. While very significant improvements have been accomplished, there is still some way to go in the full-numerical modelling of the rough-surface scattering process. In fact, what may prove to be most useful in the end is the combination of simplified analytical models with full-up simulations to produce a background-like level of clutter with highly detailed, regionally specific predictions. Unfortunately, it is not clear from the literature that there is a concentrated effort to "put all the pieces together," such as was suggested above. The pieces are there, but they need to be forged together to generate a robust data base and, eventually, an extrapolating model. So, in answer to the question of what is the state-of-the-art, the answer is that there are a good deal more pieces of the puzzle available to study and use, but they have yet to be put together.

Concerning anticipated programmes, there are really two issues. The first involves the nature of change: will it be evolutionary or revolutionary? The second is much more important, and it centres on the simple questions of whether things will change, and what will cause the change. In regard to the way things may change, it is clear to those who work in this field that the change will be evolutionary, with one exception. This exception applies to the way we numerically model the scattering from randomly rough surfaces. It appears that such modelling is on the brink of a revolutionary change in the way we set up the basic scattering problem. The change involves a reordering of the basic scattering processes that take place on the surface prior to the use of numerical techniques to solve the re-ordered equation. The promise of this method is that it will permit the solution of very large

scattering area problems without the normal increase in computer memory.

Apart from this technique, most of the other work will be essentially evolutionary. For example, the combination of random volume and surface scattering problems to predict the behaviour of foliage covered surfaces is a natural outgrowth of previous surface and volume work. The use of a strong fluctuation volume scattering theory with conventional surface theories may be necessary to predict the response of ground-penetrating radars. Probably the most difficult scenario to measure, and to predict, is the relatively low-frequency radar that responds to the surface, foliage on the surface and objects underneath the surface in the same range bin!

The more important question, from the point of view of the future, is whether the needed improvements will take place. First, it should be noted that surface clutter holds very little interest in the civilian technology market, primarily because of the low use of radar in this market. Contrary to what is published about "Intelligent Vehicle Highway Systems (IVHS)," it is highly doubtful that there will ever be sufficient use of radar in the civilian market to generate the need for further surface clutter research. Thus, the future of surface clutter research and technology is going to be determined completely by the on-going investment of the military. In short, this is a military problem, and it will remain a military problem; future progress will be totally dependent on investment by the military.

We are presently poised on the brink of some major improvements in our ability to understand and predict surface clutter, but such advances will require future investments by the military. It should be noted that the pacing items are not matters of technology, but are more dependent on funding and time.

ANNEX 4: RSTA - SIGNAL PROCESSING

Potential Improvements in Signal and Data Processing Techniques for RSTA

Signal and Data Processing is certainly the key to the development of future RSTA systems. As we have seen before, the accuracy, flexibility, and resolution of passive and active sensors are constantly increasing, and the amount of available data in real time will, by far, exceed the human processing capabilities. So the extraction of significant features, the elimination of false alarms, and the integration of all the different sensing modalities in a coherent view has to be done, whenever possible, in an automatic way; keeping, nevertheless, the man-in-the-loop in case of complex problems and/or important decisions.

MultiDimensional Signal Processing for Radar Applications

Air and Spaceborne radar will be one of the key sensors of future RSTA systems. Compared with optical/IR sensors, radar offers the potential of long-range/all-weather/ day and night operation, and penetration of smoke, dust, foliage, and ground. The agility of the electronically steered beam makes multifunction operation (search, target acquisition, multi-target tracking, classification) possible. Synthetic aperture techniques (SAR/ISAR) of air and spaceborne radar promise geometrical resolution comparable, or even in excess of, optical systems. Array-processing techniques make operation under adverse conditions (ECM, clutter, ARMs) possible. Additional features such as doppler, polarisation, interferometric, and multi-frequency operation make radar a powerful tool for target classification.

Conformal arrays are also required whenever a radar array antenna aperture has to conform geometrically to a shaped surface, such as that of an aircraft, drone, or missile, paving the way to more futuristic "Smart Skins" concepts. Conformal arrays will comply to many of the RSTA system performance properties of planar phased arrays (generally: Multifunction Radar Performance) and to important additional operational constraints, and the resulting additional requirements. However, the complexity of signal processing will be significantly increased.

In this context, Multidimensional Signal Processing techniques will play a predominant role. With the advent of super-computer power in signal processing chips, such techniques will become largely available. Significant progress can be expected in 10 to 15 years in the following fields:

- Parallel processing architectures (e.g., systolic, SIMD, MIMD) and algorithms (e.g., Higher Order Statistics Antenna Processing) for real-time (on-board) processing;
- Digital processing hardware, including programmable (in high-level languages) signal processors/dedicated hardware;
- Development and verification of signal and array processing algorithms, including LPI features (low probability of intercept), pulse compression, sequential detection, adaptive multiple jammer suppression, protection against ARM, super-resolution, air and spaceborne MTI, image generation via SAR/ISAR, and automatic image evaluation;
- Non-cooperative classification techniques, including the analysis of jet engine modulation, rotor blade frequencies, polarimetric target features, and 3-D high-resolution polarimetric images;
- Tracking techniques.

Pattern Recognition

Pattern recognition techniques are certainly the key for successful RSTA systems. Most of the military situations are characterised by the rapid and unforeseen changes of a complex and non-cooperative environment. This requires that the military pattern recognition systems be especially fast, adaptive, and reprogrammable. Robustness and embarkability constraints (weight, power requirements, et cetera) are also of critical importance. Most of the pattern recognition

system inputs are signals coming from different sensor types (e.g., acoustical, doppler, radar signals, and images from imaging sensors - ranging from IR to visible and UV). These signals must be interpreted to get usable information for decision-making processes. Due to the computational complexity of pattern recognition, the above-mentioned requirements in rapidity, adaptability, and reprogrammability have not been fulfilled entirely up until now, not even with the introduction of Artificial Intelligence techniques. High hopes are being placed on the introduction of neural networks as a new paradigm for Artificial Intelligence; because they make the link between the low-level and the high-level pattern recognition activities, their architecture is often essentially parallel, and large classes of them seem to be suited for adaptive learning and/or reprogramming capabilities. Moreover, they can provide solutions to the two main problems of Pattern Recognition: models learning, and matching between sensed data and a data base of models.

Many neural net models and algorithms have been implemented and tested successfully against more classical pattern recognition and data analysis techniques; examples include the Multilayer Perceptron (MLP) with Gradient Back Propagation, Hopfield models, Kohonen maps, and Boltzman machines for complex data classification problems, and supervised or unsupervised learning.

Further progress in techniques to build real-time, robust, reprogrammable, adaptive, and embarkable systems will make efficient Pattern Recognition Systems available for many RSTA tasks, including terminal guidance for intelligent ammunition, remote sensing, and large-scale surveillance. The development of methods to integrate numerical, symbolic, and neural network approaches will certainly help the operator not to be overwhelmed by the flows of information provided by the future "information highways," and will help him/her concentrate on efficient actions.

Fusion

The specific aspect of identity fusion may need investment for the particular demand imposed by the situation of highly manoeuvrable airborne platforms. Poor visibility in adverse weather conditions and in darkness currently restrict operation. Fusion could give an essential differential advantage over an enemy who does not have that process. The fusion process can be performed at various stages of maturity and also at various levels. Techniques employed range from statistical-based methods through to neural networks, with research pursuing a broad front. Progress is being made towards the Advanced-Vision System (AVS), which will augment the pilot's view and enhance safety. The use of vision system technology will remove some current operating constraints. Its use in civilian application is, however, limited, and is likely to remain so for some years. Currently there are two candidates for AVS: the Enhanced-Vision System (EVS), using both electro-optic sensors and radar; and a Synthetic-Vision System (SVS), which integrates navigation data from primary sensors and a digital terrain database. Forward Looking Infra-Red (FLIR) and Night-Vision Goggles (NVG) currently contribute to increased operational capability, but they require additional development.

The fusion process, which considers sensors viewing an object with different characteristics, will benefit from the availability of large data bases with short access time. The many interactions in perspective and scale for cognitively based methods improve the identification and the association of the objects. Again, considerable work is required to establish the necessary and sufficient features for acceptable times of identification. Two basic control strategies are under study, those of the weakly coupled and those of the strongly coupled. Most automated systems are weakly coupled, but system designers are attempting to emulate the inherently strongly coupled system achieved with cooperating human operators who exercise adaptive control.

ANNEX 5: HYPERSONIC AIR-BREATHING MISSILE TECHNOLOGIES

The Scramjet (Supersonic Combustion Ramjet) has been recognised as the most promising air-breathing propulsion technology for hypersonic flight (Mach number above 5), because it has a very high theoretical operational limit, depending upon the fuel used.

Considerable research has been conducted during the past ten years on the hydrogen-fuelled scramjet, with significant attention focused on new generations of space launchers. However, application of the scramjet concept using high heat-sink, hydrocarbon or endothermic fuels offers significantly enhanced mission potential for future military tactical missiles. For example, the first application of the hydrocarbon-fuelled scramjet could be a long-range (1000 - 2500 Km) missile for time-critical ground targets and strategic target recognition.

Beyond these possibilities, development of hypersonic aircraft can also be considered for global fast-reaction reconnaissance missions and for future low-cost space launch vehicles. Expected operational gains over those offered by conventional ramjet and rocket missile systems can be quantified as follows:

- Rocket efficiency: Factor of 3 - 10 improvement in specific impulse (Isp);
- Increased cruise range: Factor of 2;
- Reduced response time: Mach 8 - 1200 Km in 15 minutes;
- Affordable force multiplication: Halve missile size - launch from F-15, F-16 or 2 x bomber loadout.

The following material expands on the technical areas of importance highlighted in Chapter 8. This Annex has been divided into ten basic areas which define the critical design and/or operability issues and concerns that must be considered in order to bring a hypersonic air-breathing missile to reality. Each area addresses relevant issues/concerns and briefly describes the current state-of-the-art and known technical deficiencies/shortcomings.

Airframe/Engine Integration

For a high-speed air-breathing missile using storable hydrocarbon-fuelled scramjet propulsion, integration of the airframe and the scramjet engine is perhaps one of the most critical elements of the weapon system design. It is critical because the vehicle forebody becomes part of the air compression process of the engine, while the aft portion of the vehicle becomes part of the nozzle expansion process. As a result, proper airframe/engine integration is key to providing a low vehicle drag characteristic during high Mach number flight operation. This, when coupled with the inherent structural and weight requirements of the weapon system, causes the airframe/engine integration issues to be critical elements in the overall weapon system design. Furthermore, the application of unconventional seeker shapes and sensor windows for the missile system guidance package must also be considered as a part of the airframe/engine aerodynamic and structural design.

Propulsion System

The key to a high-speed (Mach 6 - 8) air-breathing propulsion vehicle using storable hydrocarbon fuels is the scramjet engine. One propulsion system design approach would utilise a separate rocket booster for accelerating the vehicle to Mach 3 - 4, at which time the air-breathing engine would begin to operate in a subsonic combustion ramjet mode. As the vehicle continues to accelerate to Mach 5 - 6 under ramjet operation, it would smoothly transition into the supersonic combustion or scramjet mode, where it would operate during Mach 7 - 8 cruise. An alternative approach would be to utilise a larger rocket booster to accelerate the missile to scramjet take-over flight speed of approximately Mach 5. The rocket booster most likely would be a tandem booster that would separate from the scramjet vehicle after booster burnout, although the booster could also be an integral part of the scramjet engine. In a missile system, where variable geometry would be too heavy and complex, simple two-position devices could be utilised for starting the inlet, or perhaps consumable structures could provide a temporary nozzle throat for improved ramjet operation during the acceleration phase. The forebody of the vehicle would provide some external compression for the inlet. The engine most likely would utilise endothermic fuels, which could provide more regenerative cooling capability than conventional

hydrocarbon fuels. Being able to cool the engine at the equivalence ratios required for cruise operation will, in all probability, also set the upper flight Mach number limit of the missile system. Hence, the key propulsion issues for the hypersonic air-breathing missile are engine operability at low flight Mach number and engine performance and survivability at high flight Mach number.

Cycle Optimisation

Cycle optimisation for an air-breathing hypersonic vehicle must include the integration aspects of the inlet, combustor, and nozzle, as well as the effect of the low Mach number acceleration process. In a scramjet engine, there is strong interaction between the inlet/combustor and combustor/nozzle; hence, one cannot look just at the best individual components and assume that they will provide the best performing engine. For example, one very important design parameter deals with the amount of compression done by the inlet. If compression is too low, the pressure in the combustor will be inadequate for efficient combustion. If compression is too high, recombination losses in the nozzle will become prohibitive. In addition, the scramjet missile must be able to operate over a range of Mach numbers; consequently, fixed geometry components are desirable (or at the very most, limited variable geometry). Therefore, cycle optimisation should not focus on each sub-cycle or component of the system, but rather on the global system. Optimum vehicle design can then be focused on vehicle forebody design and on the definition of an appropriate low Mach number accelerator or booster.

Inlet/Combustor Interaction

The shock wave/boundary layer interactions that occur in the region of the inlet terminal shock system for operating conditions of high relative heat release (high fuel/air equivalence ratios) in supersonic combustion are critical in determining the inlet maximum total pressure recovery and in defining supercritical stability margins. If too much heat is released without sufficient stability margin, the inlet may "unstart," resulting in a sudden loss of engine performance and dangerously high levels of pressure in the combustor. Inlet/combustor interaction is governed by fuel distribution and mixing in the combustor entrance area by the corresponding internal area distribution. Many investigators are convinced that a long isolator duct is necessary in order to separate the intake exit flow from the influence of combustor pressure rise.

Isolator duct length, however, is a controversial issue. For example, allowing for some internal pressure limitations, an engine designed with a short isolator duct may be a superior design in terms of overall integrated engine performance. Further work in this area will be required to assure an optimum inlet/combustor design.

Combustion Technology

The efficient combustion of a hydrocarbon fuel in a high-speed air vehicle must consider all aspects of on-board fuel storage, fuel feed, fuel injection, fuel/air mixing, reaction chemistry, heat transfer, flow physic, and combustion. Perhaps the most critical issues are the incorporation of proper fuel injection, fuel/air mixing, and fuel/air ignition techniques for optimum combustion within limited residence times. An additional problem may be the combustor configuration constraints resulting from the integration of the low Mach number booster acceleration engine.

An alternative combustion concept would be to use high heat-sink hydrocarbon fuels which can be decomposed via an endothermic process, resulting in gaseous fuel products that are then injected into the combustor. Research and development of high-energy endothermic fuels has been underway for several years within the US; the combustion kinetics and reaction chemistry associated with the basic endothermic conversion process are well understood.

Relative to future work in this area, a critical development issue that must be addressed is the aspect of hydrocarbon fuel and air mixing in high-speed supersonic flows essential for efficient combustion. Furthermore, influence of scale on the mixing processes should be investigated in depth.

Lastly, a large experimental data base was developed for hydrogen under the National Aerospace Plane (NASP) program, as well as specific analytical CFD codes using hydrogen-air kinetics. Similar data and CFD codes will also be required for storable hydrocarbon fuels - since most hydrocarbons have large ignition delay times and greater reaction times than does hydrogen, and thus will be inherently more difficult to burn.

Two-Phase Flow

Most hydrocarbon fuels are stored as a liquid in the missile; hence, the possibility exists for injecting a combination of both liquid and gas into the

combustor. In that the liquid fuel will be used to cool the hot parts of the engine, some of the fuel will vaporise as it cools the vehicle and engine hot parts prior to its injection into the combustor. The injection characteristics of either a pure gas or a liquid into a supersonic flow are reasonably well understood; however, little data exists for injection of a mixture of both liquid and gas (two-phase flow). Existing CFD codes cannot currently handle the injection of two-phase flows into a supersonic stream.

Engine Operability

As flight Mach number is reduced, so is total temperature and flow Mach number of the air entering the scramjet combustor. With a reduction in total temperature, auto-ignition of the fuel and air within the combustor may no longer occur; hence, some form of pilot and/or flame holding may be required. As entering-combustor-flow Mach number is reduced, the amount of heat release by the combustor will be limited before thermal choking occurs, or before pre-compression shocks are forced into the inlet, resulting in possible flow separation and inlet unstart. However, this is an operating regime where a high combustion equivalence ratio for accelerating the missile to the cruise Mach number is required. Therefore, to reduce the amount of booster engine mass required for missile launch and initial acceleration, it is mandatory that the operational range of the air-breather to take-over acceleration Mach number be as low as possible. It should be investigated as to whether the minimum Mach number operational limit can be reduced to perhaps Mach 4.5 or less. Alternatively, research should be performed on dual-mode subsonic/supersonic combustion, with special emphasis on combustion-mode transition and its attendant performance penalties, and on system global performance.

Endothermic/High Heat-Sink Fuels

Active cooling will likely be required for high Mach number scramjet missiles (Mn >6.5) designed for operational flight times of moderate duration (>5 - 10 minutes). Endothermic fuels can extend the limited thermal capacity of conventional hydrocarbon fuels by absorbing heat, while cracking these fuels into lighter molecular weight hydrocarbon gases and hydrogen. In addition to the added cooling capability offered by the fuel, the products of the decomposition process are easier to burn than the original fuel. Considerable research into the understanding, development, and application of endothermic fuels has been underway over the past twenty years within the US. In principle, endothermic/high heat-sink fuels provide the following advantages when considered for high Mach air vehicle applications:

- The increased cooling capacity offered by an endothermic fuel will permit active cooling of critical engine components and airframe/inlet forebody structures at fuel temperatures well above that allowed by a conventional hydrocarbon fuel;
- The vaporised or gaseous fuel products resulting from decomposition of the liquid hydrocarbon fuel, which can include hydrogen, greatly improves the fuel-air reaction time during fuel injection into the combustion system, and hence permits supersonic combustion of a storable liquid fuel required by engine designs of limited length.

On the other hand, the disadvantage of these enhanced heat-sink, easier-to-burn fuel products is their inherently reduced fuel specific gravity - which leads to reduced range potential.

High-Temperature Lubricants and Seals

If variable geometry must be incorporated into the engine design (inlet/exhaust nozzle) in order to meet required system performance, a simplified, affordable engine configuration must be defined that can utilise two-dimensional, two-position variable geometry components.

To protect the attendant seals and sealing surfaces from hot gas leakage, a thermal barrier of protective cold gas (of sufficient pressure) may be necessary. Hence, technologies for providing the necessary high-temperature lubricant and thermal barrier protection systems must be developed.

Actively Cooled Panels/Integrated Structures

Engine components subjected to severe thermal loads will require the incorporation of heat-resistant materials and/or active cooling. Actively cooled structures may be a design alternative to the use of high-temperature ceramic or coated carbon-carbon materials. This question is most critical with respect to structural weight, complexity, and cost. The application of actively cooled structures

demands the use of endothermic/high heat-sink fuels as the cooling means of choice.

Nozzle Chemistry/Kinetics/Performance

As flight Mach number increases, losses in the nozzle caused by flow divergence, friction, and recombination become a dominate effect on overall engine performance. Recombination losses depend upon the finite rate kinetics of the specific chemistry of the hydrocarbon fuel being used. Theoretical non-equilibrium nozzle flow investigations typically focus on either a detailed modelling of chemistry/reaction kinetics, neglecting 3-D fluid dynamic effects; or on detailed fluid modelling using a reduced thermochemical approach. As a result, deviations from experimental results may be encountered. Due to the highly non-equilibrium effects encountered in high-speed nozzle flows, both experimental and theoretical work should be brought together as closely as possible, in order to achieve optimal nozzle designs and performance.

Thermal Protection (Passive and Active)

Thermal integrity of the air vehicle and engine during high Mach number flight operation is a priority consideration. Passive thermal protection such as ablative materials, while adequate for typical flight times at Mn < 5 or for very short missions above Mn 6.5, may not be suitable for inlet surfaces, due to potential critical geometry changes as the thermal protection surface material ablates away. For longer missions at high Mn > 6.5, the combustor and portions of the exhaust nozzle will require active cooling. Critical high-heat load areas, such as the fuel injection plane and regions where strong shock patterns are formed, will also require special thermal protection consideration. However, for an affordable missile system, the associated complexity and cost of actively cooled structures must be limited as much as possible. As a result, the effective realisation of high-heat-load, thermal-tolerant, uncooled structures for high-speed missiles may depend very heavily on the successful development of advanced high-temperature, high-strength composite materials having excellent oxidation resistance.

Launch/Acceleration Booster

The scramjet engine will not operate at low flight Mach numbers, hence, a booster is required to accelerate the vehicle to Mach 3 - 4 (dual-mode ramjet/scramjet) or to Mach 5 - 6 (pure scramjet) to ensure entrance conditions to the combustion chamber which will sustain combustion operation. The principal issues then become proper integration of the booster and the scramjet combustion chamber, and propulsion mode transition between the booster phase and scramjet. The preferred solution for the booster design may be driven by the technology requirements and capabilities of either a solid or a liquid rocket booster. However, if missile launch and acceleration is to be accomplished using a solid rocket booster, the following known limitations must be considered:

- The scramjet combustor may be volume limited and, hence, may not be well suited for a design which integrates the solid booster propellant into the combustor flowpath. Additionally, the required booster propellant mass fraction may be unacceptably high for the integrated combustor/booster design in order to assure vehicle acceleration to minimum ramjet/scramjet transition Mach number;
- The application of a tandem or parallel rocket booster must also be considered. The possibility of employing a booster system consisting of both a tandem booster for initial missile acceleration, followed by an integrated booster gain for final acceleration to scramjet transition, should also be investigated.

Thermal Management

Effective management of the thermal environment generated by the engine and airframe of a high-speed missile system during flight must be handled in an integrated global fashion - the principal task of satisfying the total cooling and thermal energy requirements of the system, within the limits of the resources available to that system. For high-speed flight, engine/airframe thermal management is the proper control of thermal energy which will provide acceptable structural, material, and component temperatures throughout the entire flight. Coolant distribution systems (active-cooling systems), passive thermal protection systems (insulation, ablatives, high-temperature materials, radiation cooling), and thermal/power transfer devices (heat exchangers, pumps) for all relevant airframe and propulsion system components, sub-

systems, and structures are included in the overall integrated vehicle thermal management system. Specific issues relative to thermal management of the weapon system include the following:

- Total vehicle active-cooling requirements must match engine fuel flow requirements. If more active cooling is needed, fuel flow in excess of that required for combustion will be necessary, resulting in possible substantive vehicle range or speed degradation;
- Weapon system payload and guidance/target acquisition equipment compartments must be temperature-controlled to ensure proper operation throughout the flight of the vehicle;
- As indicated above, critical scramjet engine component areas may also require active cooling;
- Should vehicle infra-red signature for a hypersonic missile become an issue, special thermal protection and active cooling of the airframe may also be necessary. Complexity and cost inherent with an active cooling system, however, may become prohibitive in terms of ultimate weapon system affordability. Generally, the speed of such a missile (Mach 6 - 8) is considered sufficient to eliminate the need for controlling the infra-red signature of the system during flight.

Structures and Materials

Hypersonic vehicles operating at speeds up to Mach 8 represent an extraordinary challenge for structures and materials. The airframe and engines require lightweight, high-temperature materials and structural configurations that can withstand the severe conditions of the hypersonic environment. These conditions include very high temperatures, widespread heating of the whole vehicle, additional localised heating from shock waves that sweep across the vehicle during flight manoeuvres, high aerodynamic and acoustic loads, severe flutter, vibration and thermally induced stresses, and material erosion caused by the airflow across and through the engines. The engine itself represents a particularly challenging problem because of the severe environment in the flowpath involving high thermal, mechanical, and acoustic loading. As discussed earlier, in the engine, and probably parts of the airframe as well, it may be necessary to control surface temperatures using the fuel to actively cool the various components for $Mn > 6.5$.

Over the last decade, significant improvements have been made in the development of lightweight, high-temperature materials through programs underway in several of the NATO member countries. However, it is obvious that we still face many technical challenges in attempting to satisfy all the structural needs of a hypersonic vehicle. The types of structural materials used for near and mid-term applications probably will include nickel, iron, and cobalt-based superalloys, advanced refractory alloys, intermetallics, intermetallic composites reinforced with ceramic fibres, ceramic and carbon-carbon composites, and lightweight thermal insulation materials. In addition, for actively cooled structures in both the engines and the airframe, high-thermal-conductivity materials will be needed, along with materials or coatings that can survive contact with the hot fuel used for cooling. Most of these materials will require coatings to provide protection against oxidation and the other environmental conditions associated with atmospheric high-speed flight. Furthermore, advanced processing methods will be needed to produce the necessary lightweight structures that in some cases, may contain arrays of coolant passages through which fuel will flow as it controls the temperature of the structure.

Along with the development of the materials and structures themselves, structural life prediction modelling, aerothermoelasticity/loads validation, and structural life integrity methodology will be key to the successful use of the advanced materials and structures. The following briefly highlights a number of critical issues/concerns that will require close attention in order to meet the necessary materials and structural requirements for a high Mach (6 - 8) air-breathing vehicle.

High-Temperature Metals and Alloy

The high-temperature metals and alloys of interest for hypersonic airframe and engine applications include titanium alloys, titanium alloy composites, titanium intermetallics, nickel, cobalt and iron-based superalloys, refractory metals and alloys, and copper-based alloys and composites. This is not an exhaustive list, but it includes the primary classes of metallic-based materials that would be suitable for higher temperature applications in the engine and airframe. Much work

has already been accomplished on these materials for potential hypersonic vehicle application, and many of these materials have been extensively evaluated in the appropriate environments.

For airframe applications, their use would be feasible in the relatively near term. For applications in the flowpath of a scramjet engine, however, further work is still needed to mature these materials before they could be applied with confidence. This also includes the need to design and build actively cooled structures that can withstand the fuel and oxygen-rich high-temperature conditions in the flowpath. Additionally, more accurate modelling and prediction of the thermal and acoustic environments occurring in and around the engine is needed.

Carbon-Carbon and Ceramic-Matrix Composites

Carbon-carbon and ceramic-matrix composites have the potential for use as lightweight structures exposed to very high temperatures, without the need for active cooling. Because of their inherent high-temperature capability, they are regarded as candidates for use on the airframe as thermal protection panels located over the load-bearing substructure. They may also be used in a similar way in the inlet or nozzle of the engine. Much work has been done on these materials over a number of years and many practical applications have been found. However, in the case of carbon-carbon composites, effective coating schemes must still be developed to prevent catastrophic oxidation in the flight environment. Ceramic composites, on the other hand, have better inherent oxidation resistance.

For both classes of materials it will be necessary to develop methods that will allow them to survive the hypersonic environment for the required weapon system mission time. Additionally, as with all composite materials, life prediction methodology must be developed and applied to allow confident prediction of their behaviour on the vehicle.

High-Temperature Sensor Aperture Materials

For control and navigation of hypersonic vehicles, it is necessary to transmit signals through windows or apertures that are transparent to the frequencies of interest. Materials that work well at lower speeds may not perform adequately at the high temperatures seen by the skin of a hypersonic vehicle in flight. Several classes of aperture materials have been developed for high-temperature applications in ballistic missiles; however, the conditions on a hypersonic vehicle that can cruise for a relatively long duration (5 - 15 minutes) through the atmosphere may require modifications and/or upgrades of existing materials, or perhaps the development of new window/aperture material systems.

Nose Cap/Leading-Edge Materials Development

Hypersonic vehicle nose and leading-edge materials are exposed to the most severe kinetic heating. For efficient aerodynamic performance, leading-edge radii must be very small, resulting in high loading, both thermally and mechanically. Shock impingement can also lead to local heat transfer rates in excess of more than an order of magnitude for stagnation point heat transfer. Hence, materials with sufficient temperature resistance and thermal shock capability must be developed. Alternatively, leading-edge designs that might incorporate active cooling should also be considered.

Manufacturing Technology for Regeneratively Cooled Structures

As discussed above, many areas of a hypersonic vehicle - particularly in the engine - may require actively cooled (fuel-cooled) structural materials. This will be necessary in order to maintain material temperatures at levels that are within their capability. The actively cooled structures must be light in weight and must contain fine arrays of cooling passages located beneath the skin of the structure. These passages will vary in cross-section from place to place throughout the structure and will be arranged in complex configurations in order to attain maximum cooling ability. The manufacture of these cooled structures will also require significant developments in fabrication methods. These methods will include diffusion bonding, brazing, and other approaches that can lead to the needed structural configurations.

Design Criteria Development and Validation

The use of hot, load-bearing structures on the airframe and in the engine of a hypersonic vehicle

requires the development and validation of appropriate thermostructural design methods that have the capability to cope with the complex conditions that will be experienced during flight.

These design methods and predictive models must account for a variety of effects not seen in lower speed flight, including the static and dynamic thermal, acoustic, and aerodynamic loads generated as the air and fuel move at hypersonic speeds across the skin and through the engines. They must also address the particularly difficult problem of the severe effects of moving, intersecting shock fronts that can cause very high thermal and mechanical loading in localised areas. In addition, the heating caused by discontinuities in the flow path, such as gaps between panels, fuel injectors, support struts, et cetera, represents a very difficult challenge for available modelling and prediction methods.

In general, while current methods provide a basis for designing hypersonic engines and vehicles, they cannot fully predict all the conditions that would be experienced in flight through the atmosphere for long mission times at speeds above Mach 4, and in particular, cannot define the full set of detailed conditions inside the scramjet engine. The development of suitable design methodologies is crucial to the successful use of materials and structures in a safe, reliable, affordable manner, as is the validation of design methods in realistic test environments that can simulate the extreme conditions of hypersonic flight.

Computational Analysis/Design Code Development

The effective development and application of critical design codes and analysis tools are key to the successful development of a Mach 6 - 8 missile using a storable hydrocarbon-fuelled scramjet propulsion system. In that the scramjet engine is an integral part of the weapon system, vehicle external aerodynamics, the air intake system, and the exhaust system must be well understood, in order to optimise propulsion system performance capability and minimise vehicle drag losses throughout the flight envelope. Hence, the ability to analytically describe the air vehicle and propulsion system is critical to meeting the design requirements and mission goals of such a missile system.

CFD Improvements

Many Computational Fluid Dynamic (CFD) codes exist for the analysis of hydrogen-fuelled scramjet engines. What is needed for the hydrocarbon-fuelled scramjet engine is hydrocarbon kinetics models, to include the possibility of two-phase flows. Current kinetics models consist of several hundred reaction equations, all of which must be solved numerically. It is unlikely that complete reaction sets will be practical for use in 3-D CFD calculations, due to the excessive computer time required; however, a simplified set of reactions, along with their rate constants, should be developed and validated for CFD use.

Existing computational codes that are commercially available suffer from a lack of correct aerothermodynamic modelling. Highly non-equilibrium flows cannot be represented with most of these codes. Furthermore, they are not able to accurately represent regions of mixed flow (i.e., subsonic, transonic, and supersonic) which are typical in dual mode ramjet/scramjet engines, including interactions between the supersonic free stream and the local near-wall subsonic/recirculating flowfield.

Additionally, the upstream influence of pressure rise within the scramjet combustor cannot be adequately modelled. Therefore, it is necessary to provide, within the near future, commercially available advanced computational design and analysis tools which are capable of performing these tasks based on reliable validation data obtained from well-defined experiments.

In addition, it is essential that these advanced computational design and analysis tools be integrated into advanced simulation systems capable of modelling the entire propulsion system, including component interactions at multiple levels of fidelity from one dimensional to three dimensional. These simulation systems are required to evaluate multiple propulsion system concepts and to enable a concept downselect process to a fewer number of optimised systems, which would then be designed and tested. This simulation capability would also enable significant reduction in the time and cost of designing, developing, and testing the hypersonic propulsion system, essential for an affordable system development program.

Work is currently underway to develop general architectures and critical communication and management links, but much more work is

required. Work in developing the models that capture complex shock interaction fluid dynamics and combustion physics, as well as the much higher degree of interaction among components in the hypersonic propulsion system, particularly between inlet/combustor and combustor/nozzle elements, is required. Multidisciplinary integration and optimisation techniques need to be developed and incorporated into these simulation systems in a computationally efficient and modular fashion to enable multiple organisations to incorporate specialised, and perhaps proprietary, analysis and design codes into the system simulation methodology.

Turbulence Modelling (Compressible Flows)

Turbulence modelling is perhaps the most uncertain topic of fluid dynamics still under development. For example, the well-known k-ε model must not be used for highly compressible flows that occur with high-speed aerodynamic flowfields or within chemically reactive flows, unless it is modified to account for compressibility effects. Other models compensate for this insufficiency but are only applicable to a narrow band of problems. Even newer developments have not been promising. It is well known that tremendous differences exist between high-speed laminar and turbulent flows. These must be properly modelled in order to effectively apply CFD as a performance prediction and design analysis tool for high-speed air-breathing propulsion. Consequently, turbulence modelling should be regarded as the most important issue within the context of CFD. Additionally, extended experimental and theoretical research is strongly recommended, in order to provide more reliable theoretical models and/or experimental/semi-empirical correlations. Furthermore, experimental validation of these models and analysis codes in realistic supersonic combustor designs is required.

Inlet-Shock/Boundary Layer Interaction/Transition/Prediction

The effect of shock wave/boundary layer interaction on engine inlet performance is of great importance for hypersonic air-breathing missiles. Inlet-shock/boundary layer interactions include reflected shock interactions, corner-flow shock interactions, and oblique shock reflections, including separation effects.

One of the most critical airframe/engine configuration issues is the necessity to design an inlet of limited length, but with an oblique shock structure which can exceed the reflected shock wave separation limits by a considerable extent. Inlet compression is typically accomplished with a long external compression forebody, followed by an inlet cowl which generates an internal shock field. As a result, the highly viscous boundary layer entering the inlet will be subject to strong pressure gradients and, at some point, may separate. Consequently, the effects of shock/boundary layer interaction in the vicinity of an expansion corner is an area of particular concern and requires fundamental investigation.

Another special question is whether a series of oblique shocks can be tolerated without causing an inlet unstart. State-of-the-art experiments can be accomplished in either short-duration experiments using cold structures (but where heat transfer is not represented correctly), or with quasi-stationary small-scale testing (but where total temperatures and Reynolds numbers are not adequately simulated). To overcome the aforementioned deficiencies, flight testing of adequately instrumented engines of sufficient scale is required in order to effectively validate computational predictions.

In order to optimise vehicle flight performance, a sound understanding of shock boundary layer interaction and boundary layer transition and separation must also be known. It is important that design analysis tools and codes be developed that can accurately predict the flowfield characteristics around the forebody and scramjet engine inlet in terms of boundary layer transition, separation, and shock field interaction. Today, the prediction of boundary layer transition is done by linear and non-linear stability analysis, using simplified flow models. The results obtained are promising when applied to flat-plate boundary layer flows with or without downstream pressure gradients and adiabatic walls. These simplified flow models, however, are unacceptable when dealing with complex geometries.

Furthermore, due to the mathematical complexity of the governing equations, there is no expectation that reasonable predictions can be made for the more complex flow systems. Even empirical results show considerable deviation for the same free stream Mach number, based on free-flight testing and wind tunnel experiments. Consequently, the

acquisition of good experimental data correlated with theoretical approximations from stability theory is essential for the designer's ability to understand and predict flowfield boundary layer development, transition, and separation.

Flow Diagnostics, Sensors

Within the supersonic flowfield, intrusive diagnostic measurement methods are not recommended because of their heavy influence on the main flowfield parameters and the severe thermal environment. Robust, non-intrusive, laser-based diagnostics should be developed which can be applied, not only to laboratory problems, but also to more complex and realistic engine geometries. For example, laser diagnostic measurement techniques should be developed in order to obtain full-planar, rather than single-point only, measurements for accurately characterising high-temperature flowfields. Additionally, integral quantity measurements related to engine performance should be developed, e.g., metric balances and metric strips. Non-intrusive temperature and pressure sensitive paints should also be further developed and applied to selected areas/components of the air vehicle.

Configuration Optimisation

This issue focuses on the need for effective analysis and design codes that can provide design trades in order to arrive at an optimum vehicle configuration design suitable for the expected flight mission. Configuration optimisation is a joint analysis effort which includes engine propulsion, vehicle aeromechanics, and seeker/sensor dynamics. Both cost and weight implications can enter into this area in arriving at an optimised weapon system design. Furthermore, better models of cost estimation, including manufacturability and maintainability, are needed to ensure that the optimised configuration will result in an affordable, lower life-cycle cost system. Since over 90% of the final cost of the propulsion system is determined in the preliminary design and configuration selection phase, it is essential that better tools are developed to estimate the total system cost during the early system decision phases. This is particularly challenging for new materials and highly integrated structures, which require development of new manufacturing and maintenance processes. Finally, it is important that these models be developed concurrently with, and are incorporated into, the advanced simulation system discussed above.

Weapons Separation

In that a high-speed air-breathing missile system could be air-launched, it is important to understand the aerodynamic loads the launch vehicle may impart to the missile during separation. Hence, the ability to effectively analyse the flowfield around the missile during separation is very important. Furthermore, in the case of an air-launched vehicle, the classical external hanger array is by no means acceptable due to the local kinetic heating and severe drag increases inherent with hypersonic flight. Consequently, retractable hangers and plugs are mandatory for hypersonic vehicles.

Weapon System Guidance and Tracking

In order for a high-speed air-breathing missile to be an effective and accurate weapon system, technologies in support of missile guidance, targeting, tracking, terminal or end-point accuracy, and mission simulation and testing are very important. At speeds of Mach 6 - 8, global positioning information of the weapon and the target are critical elements of the mission equation. Hence, the following critical issues/areas must be addressed.

Global Navigation Satellite System (GNSS)/ Inertial Navigation System (INS)

The performance of GNSS, particularly when integrated with inertial sensors, is not in general limited by platform velocity. The GNSS receiver and integration design, however, must take into account the platform's acceleration profile so that its dynamics do not exceed tracking loop bandwidth. This is routinely conducted for any integrated multi-sensor navigation system. Although ionisation effects at the skin of a hypersonic vehicle, for extremely high velocities (greater than Mach 12) such as those encountered on re-entry vehicles, can inhibit all radio navigation or communication capabilities, this issue is not expected to be of concern for the flight velocity envelope (Mach 6 - 8) under consideration for this air-breathing missile.

Targeting/Tracking Control System Logic

The operational utility of hypersonic weapons will depend directly upon the ability to provide accurate and timely targeting data to a variety of weapons

delivery platforms. Targets that may require rapid response include Tactical Ballistic Missile (TBM), aircraft, manoeuvring units, long-range artillery, air-launch rockets, and missile boats/ships. Some of these targets, in particular relocatable TBMs, may be situated hundreds of miles inside hostile territory and may evade detection by mobility and countermeasures. Therefore, the use of Autonomous Target Recognition (ATR) techniques by long-range, high-speed, low-observable unmanned air vehicles are critical. This targeting data must be timely enough so that weapon launch can occur within seconds-to-minutes of target detection. Also, it must be accurate enough to allow weapons equipped with Global Navigation Satellite System (GNSS) receivers and Inertial Navigation Systems (INS) to achieve high probability of kills against soft targets. Hard, point, or moving targets require terminal seekers given the low Circular Error Probable (CEP) required to defeat these targets. However, the targeting data must still be precise enough to allow a transition from GNSS/INS navigation to terminal guidance.

Hypersonic weapons with a terminal seeker may also use ATR for target detection, identification, and aimpoint selection, without Man-in-the-Loop (MITL) operation. Additionally, moving targets will require hypersonic weapons which can receive in-flight targeting updates. Consequently, the targeting and tracking control system logic for a hypersonic weapon is a critical design issue requiring the effective integration of on-board sensors, receivers, and navigation techniques to permit a rapid response against a hostile target.

Lightweight High-Energy Batteries

Electrical power for a high Mach missile system is a critical element of the weapon design. High-energy batteries will be required to provide power for the guidance and control subsystems, the air vehicle control actuators, and the warhead arming and sensor systems. These batteries must be lightweight, high-energy units capable of meeting all the power requirements of the weapon system for the duration of the mission. They must also be shock resistant and tolerant of the high thermal loads generated within the vehicle during flight.

Air Vehicle/Propulsion System Thermal Management Integration

As indicated earlier, thermal management throughout the entire high Mach weapon system is a critical design issue and is of paramount importance with respect to missile guidance, targeting, and tracking requirements. The on-board sensors and GNSS or INS receivers must be protected from the severe thermal environment generated by the vehicle during flight. On-board equipment compartments and warhead electronics must be maintained at a temperature level consistent with the operational limits of the electronic sensors contained therein.

Mission Simulation and Testing

Simulation plays an important role in the development and mission application of high-speed vehicles. For the effective development of a high-speed vehicle, simulation models are required to predict and to optimise the performance of the guidance and control sub-systems. For this type of simulation, the models should represent highly accurate and detailed mathematical descriptions of the dynamics of the vehicle. This includes accurate data on the vehicle aerodynamics, propulsion system, sensors and control systems, as well as possibly complex mathematical expressions that must be evaluated by the simulation computer. These simulations are performed in a rather isolated way, in the sense that they are performed for individual vehicle developments. The simulations, therefore, do not have to fit in a wider hardware or simulation environment. Furthermore, computing time is not critical.

In the area of mission application of operational vehicles, simulation models are required to provide accurate data on overall weapon system performance in terms of speed, distance travelled, manoeuvrability, and accuracy. However, these models may be less detailed as far as on-board sub-systems, vehicle aerodynamics, sensors, guidance and control systems and propulsion systems are concerned. Such simulations may be performed to evaluate isolated missions for high-speed weapon systems. However, these simulations will also, and preferably, be used in mission management systems. This implies that the simulation models must comply with interface requirements set by the management system environment.

The critical issue for both types of simulation methods described above is the accurate modelling of the air vehicle and its sub-systems, in particular the propulsion system. Accurate aerodynamic data must be obtained by advanced computational fluid dynamics and experimental verification. Unfortunately, the propulsion system design is not fully available when development starts;

consequently, a mathematical description of the propulsion system will be developed during the propulsion system design period.

On the other hand, if this design information can be made available, the generation of the required simulation models should be fairly straightforward. This may, in turn, result in the development of the simulation models required for guidance and control system development, as well as for mission simulation. Computer power to perform the necessary calculations is not expected to be a problem. Additionally, the expanded memory and computing speed required for simulation programs of this type are also progressing well and should not be a problem.

Stability and Control

For an air-breathing missile accelerating to flight speeds of Mach 6 - 8, the ability to provide effective control and stability of the air vehicle is critical throughout the mission. Hence, the design of the flight vehicle control system and its ability to provide stable operation during the low-speed, acceleration, and cruise points of the mission, will require particular attention during weapon system design. For example, stability and control of the missile during flight can be strongly affected by airflow entry forces on the vehicle inlet system. Subtle changes in vehicle attitude and angle of attack can very seriously affect the stability and performance of the missile during flight. The flight control system will require powerful control surface actuators in order to overcome the aerodynamic loads encountered during high Mach flight. These actuators need to be compact, lightweight devices, perhaps electrically driven. Additionally, conventional flight control by the actuation of fins on a hypersonic vehicle can result in very high local heat transfer rates in the fin area. Therefore, the possibility of replacing the fin actuation system with a lateral side thruster attitude control system should be investigated. The potential for using ram-air for lateral side thrust pitch and yaw control should also be explored as a flight control system design alternative.

The direct measurement of the attitude (α,β) and velocity (Vo) of a vehicle flying at high speed, using an anemo-baro-clinometric system, can be difficult at high Mach numbers. Consequently, for vehicle navigation and engine control functions, it may be necessary to develop new technical solutions; e.g., laser-based velocimeters. Such measurement devices are already available at the laboratory level and have been applied to some helicopters and subsonic aircraft; application to hypersonic vehicles, however, must still be investigated. Additionally, the hypersonic vehicle guidance system must take into account new flight constraints, such as the effects of the propulsion system on the airframe.

Hence, new control law methods must be investigated, for example:

- Multiple targeting methods,
- Parametric optimisation-based methods using various optimisation kernels; e.g., first order methods (projected or reduced gradient, ...) or second order methods (quasi-Newton,...),
- Sensitivity matrix (or Γ-guidance) methods,
- Collocation methods.

Additionally, in order to be compatible with real-time computational constraints, one should also investigate parallel computing techniques, from both the numerical analysis standpoint as well as the hardware and software architecture aspect. Relative to the vehicle control function, the principal challenges include:

- Vehicle trim as a function of flight Mach number, on-board fuel load, vehicle centre of gravity, et cetera;

- Stability and control accuracy requirements relative to the trimmed vehicle angle of attack set-point;

- Control of fuel sloshing and vehicle structural bending modes.

Of course, sensors, computers, and control surface actuators required for vehicle guidance, navigation and control must be designed to withstand the severe hypersonic environment generated within the vehicle during hypersonic flight. Again, the importance of engine/airframe thermal management becomes a critical design issue.

Sensors and Sensor Windows

The ability of a hypersonic missile system, operating at Mach numbers in the 6 - 8 range, to effectively locate and destroy its designated target depends very heavily on the accuracy, sensitivity, and responsiveness of its sensor systems. Of

particular interest is terminal, or end-game, sensor accuracy. In this regard, an all-weather terminal guidance sensor has a minimum operating wavelength of about 3 mm (W band) for acceptable atmospheric interactions. This leads to an angular resolution of 3/D (where D is the aperture diameter in mm). Terminal sensor accuracy may be improved (3 to 30 times) from this angular resolution value through signal processing, performing both target-to-background contrast enhancement (high-range resolution, or Doppler analysis) and antenna processing (mono-pulse or others).

Technology developments in these areas have shown promising capability improvements for low-speed missiles or munitions. However, at hypersonic speeds, additional improvements to the sensor package design may be necessary. For example, the sensor window material must be able to sustain high temperature, with limited dielectric modification; furthermore, window shape could produce high values of aberration directly limiting angular accuracy.

Consequently, sensor technology is critical to the successful development and deployment of a hypersonic air-breathing missile. The environmental conditions, in and around the sensor electronic and optical systems, can be critical to effective sensor operation and integrity. The sensing equipment must also be lightweight, robust, and thermally and vibration/shock insensitive.

Aerodynamically Configured Vehicles -Waveriders

To obtain maximum range, it is important to have an aerodynamic vehicle with a high lift/drag ratio, while at the same time producing a reasonably uniform flowfield for the scramjet propulsion system.

Unconventional airframe shapes offer the most promising aerodynamic performance characteristics relative to lift/drag ratio for a hypersonic vehicle. For example, the Waverider concept can potentially provide the best performance in terms of range, and if designed with reasonable volumetric efficiency, can offer an attractive scramjet propelled vehicle design. Consequently, the Waverider vehicle design should be given serious developmental consideration for a hypersonic missile.

Weapon System Test and Evaluation (T&E)

Key requirements for test and evaluation of a hypersonic air-breathing missile exist in multiple design areas, from the component to the integrated system level. Tests at all levels of design and integration must closely interface with computational modelling, both for prediction and verification of results. This necessitates a building block approach in which component level computational models provide performance predictions which are verified through testing. The resulting information is then used to predict sub-system performance, which in turn is verified through an appropriate level of ground and/or flight tests. Testing, and its associated diagnostic tools, must be geared to reducing uncertainty and to verifying computations at each level, including the integrated system level. The baseline for this methodology must be reasonably achievable in the near term, implying only moderate upgrades to existing test facilities and diagnostics, and minimising new dedicated test capabilities. Existing T&E capabilities may be adequate for certain component and/or subscale evaluation of a hypersonic missile; however, improvements to both ground and flight T&E capability are required.

Remote, real-time coupling of computational analysis tools and advanced simulation systems to both ground and flight T&E facilities is also required, to enable rapid assessment of the test results and real-time test modifications. Current work has demonstrated the feasibility of using advanced communication satellites to transmit large amounts of data for a propulsion component with sufficient speed to remote sites, enabling essentially "virtual wind tunnel" capability anywhere in the world. More work is needed, however, to demonstrate that this capability is feasible for a complex propulsion system. This capability would enable a new level of international cooperation to become a practical reality.

Propulsion

Uncertainties in engine operability, survivability, and performance in the hypersonic regime drive the need for full-scale ground testing, with run times on the same order as flight. Deficiencies exist in both scale and run time with current ground test facilities.

The influence of scale on fuel mixing requires in-depth investigation. Characterising the

thermodynamic properties and chemical composition of the test medium, and its affect on propulsion, is critical and should be accomplished early on. Verification of combustor turbulence and fuel injection and mixing models is also critical. A test methodology involving the fuel control and active-cooling systems must be developed. Booster/ramjet/scramjet mode transitions are critical, requiring specific facility operating conditions.

Airframe/Engine Integration

The strong coupling between inlet and engine performance, in combination with the afterbody contribution, necessitates a propulsion test facility which can accommodate an integrated inlet/engine/aft-body at full scale and at representative exhaust altitude conditions. Flight test of the airframe/engine sub-system may be a key risk-reduction measure, requiring development of a host platform to achieve ignition and cruise conditions.

Thermal Management

Ground test facilities must accommodate propulsion system operation with active cooling mechanisms, including actual or representative fuel control and airframe cooling effects. At a missile scale, a fully integrated vehicle test may be feasible that would reduce risk in the areas of thermal management and propulsion operability and performance. Methods of simulating thermal "trajectories," consistent with expected mission profiles and operating scenarios, are also necessary.

Structures and Materials

These test requirements are strongly tied to those of the propulsion and thermal management systems. Aerothermal test capabilities exist in high enthalpy arc facilities and aerothermal wind tunnels for subscale and limited full scale testing. Facilities must be able to approximate the thermal and acoustic environments during propulsion system operation. Critical flight-weight hardware must be evaluated under conditions comparable to those of early operability tests. In addition, aero-optic tests can be used to verify sensor window properties and capabilities under these conditions.

Stability and Control

Well-established methods of integrated modelling, ground test and flight test should be applied to stability and control evaluations. Subscale wind tunnel tests and computational simulations may employ models equipped for multiple attitude control configurations, including lateral thrusters. Limited full-scale stability tests during airframe/engine integration testing may be feasible, although facility modifications are probably required. Flight test of a "stability and control" test vehicle would help bridge the gap between propulsion flight tests and a full-up guided missile test, providing an airframe/autopilot evaluation through in-flight separation and pre-programmed manoeuvres.

Guidance and Tracking/Mission Simulation

Ground-based evaluations of the integrated sensor/navigation/guidance sub-systems will be highly iterative, as increasingly accurate aerodynamic and propulsion models are built. Hardware-in-the-loop testing will be central to design iteration and verification. Closed-loop tests, with navigation processing, mid-course guidance updates, and terminal seeker views, are critical. Eventual flight tests of a complete missile system, including all guidance and navigation components, will provide mission verification in an operationally representative environment. These flights must be properly phased with preceding test and simulations in order to effectively incorporate significant design changes, and they must be geared to supporting the mission simulation effort.

ANNEX 6: REUSABLE SPACE LAUNCHERS - NATIONAL PROGRAMMES

This annex describes reusable launcher programs on-going in Europe, the US, Russia, and Japan. Additionally, it describes technology fallouts - advanced technologies that will have impacts in many other fields, should be proven by these programmes.

US Programmes

Recently initiated hypersonic programmes have resulted in a substantial recovery of activity in hypersonics in the US. The programmes are articulated as follows:

- Space access programmes are led by NASA, and simultaneously address two generations of reusable space vehicles:
    * The rocket-propelled vehicles are the first generation, with the goal to reduce the recurrent specific cost into orbit by one order of magnitude; the programme is called RLV, for Reusable Launch Vehicle.
    * The air-breathing propelled vehicles are the second generation, with the goal to reduce the specific cost by two orders of magnitude. Several efforts are being made in this direction; one is already at the stage of in-flight technology experimentation. This programme is called Hyper-X.
- Hypersonic cruise vehicle technology developments are led by the Air Force, with applications both to missiles and spacecraft, and consideration to military space access and global aviation potentials. This effort takes over from the NASP single-stage-to-orbit, air-breathing demonstrator programme, which was discontinued but prompted many technology advances. The programmes are focusing on air-breathing vehicles with endothermic or mixed liquid hydrogen/hydrocarbon propellant. These programmes are HyTech, and the dual-fuel air-breathing hypersonic vehicle study.

US Reusable Launch Vehicle Programme

The programmes purpose is to mature and demonstrate technologies leading to a viable commercial launch system that also satisfies governmental mission needs.

The Reusable Launch Vehicle programme efforts are focused on the concept of all rocket propulsion, fully reusable single-stage-to-orbit.

This system concept was identified in the NASA "Access to Space" study, completed in January 1994, as being achievable in the near term. This study recommends the concept to be used for the Space Shuttle replacement by the year 2008.

This Reusable Launch Vehicle technology programme started in 1994. It included an Advanced Launch Technology programme that supports the design, manufacture, and ground test of the following key technology elements, needed for an operational Reusable Launch Vehicle:

- Reusable cryogenic tanks,
- Graphite-composite primary structures,
- Advanced thermal protections,
- Advanced propulsion (including an in-flight aerospike engine test on an SR71),
- Avionics and systems.

Additionally, it included three experimental vehicles, which incorporate the above technologies for their in-flight demonstration.

The initial purpose of the DCX-A (a Vertical Take-off/Vertical Landing rocket vehicle programme) was to demonstrate low-cost simplified flight operations, rapid turnaround, and the vertical take-off/vertical landing concept. In the frame of the Reusable Launch Vehicle activities, it has been upgraded to incorporate some of the advanced technologies; such as, the Aluminium-Lithium LO2 tanks, the graphite-epoxy LH2 tanks, composite structures, and advanced sub-systems. The vehicle has performed a large number of flights and fulfilled its objective. The failure which occurred at the last flight cannot be attributed to the main technology challenges of the programme.

The X-33 vehicle is a sub-orbital demonstrator, whose purpose is to demonstrate the feasibility of

the key technologies enabling the design of a SSTO rocket launcher. Three consortia were awarded competitive contracts for its pre-definition phase, (Rockwell, McDonnell/Boeing, and Lockheed Martin) exploring, respectively, a wing/body Vertical Take-off Horizontal Landing concept; a Vertical Take-off Vertical Landing, ballistic-shaped rocket, and a Vertical Take-off Horizontal Landing lifting body.

The decision to award a single contract to Lockheed Martin for design, fabrication, and flight testing of the X33 by early 1999 was made in mid 1996, at a cost of US$ 941M. Significant additional financial contribution is expected from the contractor. A decision on whether to design and build an operational launcher based on X33 technologies will be made by the involved companies by the year 2000.

The X-34 vehicle is a small, reusable sub-orbital test vehicle. The objective is, starting in fall 1998, to conduct test flights to Mach 8 and 250,000 feet, and to validate techniques for achieving high flight rates - up to 25 per year. It must also demonstrate technologies which are applicable to future reusable launch vehicles. A team led by OSC has been selected by NASA for a contract to carry out the work, at a cost of US$ 50M. An additional US$ 10M will be spent in government organisations on the project.

Hyper-X Programme

The goal of the Hyper-X programme, led by NASA Langley and Dryden, is to demonstrate, in flight, hypersonic air-breathing propulsion technologies. The vehicle is unmanned; its engine is a liquid hydrogen-fed scramjet.

In a first phase, four demonstrators will fly by 1998, at increasing mach numbers from 5 to 10, at approximately 100,000 feet. The vehicle is initially boosted by a Pegasus first stage, which is dropped from a B-52 at 40,000 feet. It will be, by far, the fastest air-breathing plane ever flown world-wide; however, it will not be recovered.

The next phase will be experiments, in flight, with a reusable air-breathing hypersonic aircraft. The propulsion may be a rocket-based combined cycle, in order to further improve the specific impulse and open applications to the second generation of reusable space launchers.

Hytech Programme

The objective of the US Air Force is to develop the technologies needed for a hypersonic cruise missile of 1.5 T, flying at Mach 4 - 8, over a range of 750 NM and using a hydrocarbon-fuelled scramjet.

These technologies will first be demonstrated on the ground, including some full-size hot-wind tunnel experimentation. However, a demonstrator programme may be envisioned to start in the year 2002.

Dual-Fuel Air-Breathing Hypersonic Vehicle Study

This study allowed the predesign of multiple vehicles having in common the use of air-breathing, mixed hydrocarbon/hydrogen propulsion. The applications envisioned were the global reach/global strike from CONUS, missiles, and military cheap access to space. One of the main conclusions is that a Mach 10 vehicle, that provides a global reach from CONUS for fast reaction with high survivability, is feasible. It, however, involves a conventional in-flight refuelling on the return leg.

Future European Space Transport Infrastructure Programme (FESTIP)

The main objective for Europe is to remain competitive in the long term on the launchers market. Beyond the Ariane 5 improvements, a technology development programme called FESTIP is under way in order to prepare the future European reusable launchers. These launchers are expected to allow a drastic reduction of the recurrent launch costs, a simplification of launch operations, more flexibility in the preparation and execution of the missions, much shorter times to respond to launch requests, an increased reliability, and a mission-abort capability.

Europe has not yet identified which system concept is most likely to satisfy its specific needs. System work is therefore organised to achieve this system concept selection by 1998. The technology development efforts would then be focused on this concept, as the US did in early 1994 when selecting the SSTO rocket system concept as baseline.

The FESTIP studies were started in 1994 and build on previous European and national efforts: Winged-Launchers studies, Sänger project, HOTOL, and many others. The FESTIP work comprises a system study contract to DASA for 13 MAU and several major contracts, covering generic technologies (aerothermodynamics, materials, structures, propulsion, and heat management), for a total of 7.5 MAU. The first FESTIP programme phase terminated at the end of 1996; continuity is ensured with the next phase, which covers the period 1997 - 1998.

The plans for FESTIP 1997 - 1998 include a system slice which intends to progressively narrow down the concept options on which could be developed the first European reusable launcher. Technology requirements attached to the potential concepts will be quantified. In parallel, several technology development slices are foreseen to develop and test on ground samples and assemblies representative of the key technological difficulties. Predesign studies will be made of a flying test bench to experiment in flight operations and reusability. Initial flights of this demonstrator are expected in 2001; its flight domain is then planned to be progressively expanded from supersonic toward hypersonic speeds.

Russian ORYOL Future Launchers Programme

A research and development programme called ORYOL (Eagle) is presently running in Russia. Its purpose is to prepare the next generation of Russian launchers. While the cost reduction of launches is an important factor for Russia (their objective for recurrent cost reduction is between 2 and 7 depending on the technologies involved), other equally important factors are an increased flexibility and reliability for the launch operations, the possibility to launch from, and recover to, the Russian soil, on any orbit of interest, and the protection of the environment (avoiding the fallback of chemicals and of first stages on their soil). Reusability is only a parameter in the Russian studies, and partial reusability is considered as a valid intermediate step. The future launchers are expected to respond first to national needs and priorities, which include the elaboration in space of manned orbital stations and their supply with crew and cargo. The commercialisation of the launch services is, so far, not seen as the initial driver for the definition of their future launchers, which are expected to be manned, and aim at payload capabilities much larger (between 14 and 25 tonnes to a space station) than their equivalents in the Western world. However, the technical challenges are of the same nature. International cooperation is readily considered by Russia to ease their development effort, and has already started with Europe.

The ORYOL programme deals with both the elaboration of system concepts and the preparation and validation of supporting technology (materials, structures, and propulsion). It builds on previous work including Energia/Bourane and MAKS (Multipurpose Aerospace System). It involves more than 15 research and design organisations in Russia. The system studies are led by TSAGI, for horizontal take-off concepts, and TSNIIMASH for vertical take-off concepts. The development of advanced rocket propulsion is the responsibility of NIITP (Keldysh Institute), while the air-breathing propulsion is headed by CIAM. Combined propulsion is being addressed by both companies.

Flight technology demonstrator projects are considered in Russia. One of the most advanced proposals is a vehicle called IGLA (needle), which has already flown, and is proposed by CIAM as a support for the integration of more advanced technologies. This vehicle is proposed to demonstrate in-flight RAM/SCRAM propulsion from Mn 6 to Mn 14. There are also other proposals for air-launched demonstrators.

An important technology basis and design capability still exists in Russia; but the future of the advanced launchers seems uncertain, unless it is performed in the frame of an international cooperation. If the political changes in Russia can restore the strength of their industry, and if they are pushed by strong military requirements, very advanced launcher projects could concretise soon. With enough funding, they have the technical capability to proceed very fast to large, advanced operational launch vehicles.

Japanese Activities Towards Reusable Launchers and Space Planes

Japan presents their long-term space development plans as a Japanese contribution to routine space

access for the benefit of mankind. This vision is indeed shown by repeated attempts to create international collaborations around Japanese projects. The reduction of the cost of Japanese launches has recently been declared as a priority goal, and NASDA foresees large investments to upgrade the H2 launcher toward the cheaper H2A version. This reduction of cost is presented as a domestic concern, not as an attempt to offer a new competitive launcher on the market.

In parallel, NASDA is financing the development of the Hope-X mini-shuttle, to be launched by the H2A in the year 2000. This shuttle is automatic and has no payload capability. Its purpose, according to NASD, is to contribute to the demonstration of the technologies necessary for future unmanned orbital spaceplanes.

The development of future orbital reusable spaceplanes, which are intended to reduce, by two orders of magnitude, the cost of access to space and make it more flexible, is a declared goal in Japanese space policy. The implementation of this goal, which, in the end, is considered as an international cooperation effort, began with the Spaceplane programme in 1997. The long-term plan forecasts an expense of 2 trillion yen over the next 15 years to upgrade H2. It is worthwhile to mention that, so far, no space programme has ever been cancelled in Japan before its completion. System concept studies on reusable concepts started in 1989, and wind-tunnel testing has been performed. Both single-stage and two-staged-to-orbit (SSTO and TSTO) reusable launchers are considered. The SSTO is a manned air-breathing concept.

In the frame of the ATREX programme, since 1988 Japan has developed an advanced air-turboramjet engine capable of flying in the Mach 0 to 6 range. Static and wind-tunnel tests have been performed, and flight testing is planned up to the year 2000. The applications of this engine are not clear; it could serve on the first stage of a TSTO, and presents an obvious military potential. As an alternative concept, the Liquid Air Cycle Engine has also been studied, and good progress has been made - including tests on a heat exchanger that drives the mass of this kind of engines.

Technology Fallouts

Reusable launchers are not feasible or practical unless a number of advanced technologies, presently under development, can be applied with confidence to aerospace vehicles. Some of the enabling technologies have direct applications to improving the performance or reducing the cost of conventional military air or space vehicles. These technologies are listed below.

Composite Primary Structures

These are already used for military aircraft. Larger parts are required, with relaxed tolerances for their conditions of utilisation. Non-Destructive Inspection and composite repair methods need to be developed, as well as permanent in-flight health monitoring to implement an optimised maintenance (no systematic disassembly for inspection during periodic visits).

Lightweight Sub-Systems

Weight must be saved on sub-systems and on equipment that are similar to those used on military aircraft, such as flight control sub-systems, batteries, landing gear, et cetera. High reliability is required despite the aggressive environment.

Aluminium-Lithium Cryogenic Oxygen Tank and Graphite Composite Cryogenic Hydrogen Tank

Both of these technologies represent an extension of the utilisation conditions for materials presently used in military aircraft.

Lightweight Reusable Thermal Protection Systems

New hot structures need to be developed that sustain a large number of thermal cycles without any maintenance. Durable anti-oxidation coatings, and new sealing and bearing devices are required. This field of research presents some overlap and synergies with high-performance military engines. Durable, low-cost turbine discs with increased temperature could benefit from thermal protection development efforts.

Air-Breathing Hypersonic Propulsion

Air-breathing propulsion is one of the possible options for the initial acceleration of reusable launchers; this technology field, which includes RAM, SCRAM, and air-augmented rockets, is common with hypersonic weapons. The fuel type may be different according to the application

(liquid hydrogen, hydrocarbons, endothermic fuels, mixed fuels).

Tri-Propellant and Other Advanced High Thrust-to-Weight Ratio Rocket Engines

This type of propulsion is another possible option which can be used from ground to orbit. It does not seem to have applications globally, other than for orbital vehicles. However, the advances required for the development of its individual components may also have other aerospace fallouts.

Artificial Intelligence Health Management

Reusable launchers are unmanned vehicles that perform autonomously complex missions. They must be able to cope with hostile environments without the support of the judgement of men, in real time, taking into account non-nominal conditions, including failures and degradations of the vehicle. The artificial intelligence which needs to be developed for these vehicles is much comparable to what will be required for unmanned military aircraft operating in a hostile environment.

Other Spin-Offs at System Level

Rapid prototyping methods for hardware and software, fast-track, lighter management methods, as well as a new role-sharing between government and industry, are extremely important for the actual reduction of cost aimed at by future reusable launchers. The methods pioneered for the DCX development need to be scaled to more important programs. These programs will serve as test grounds for management methods applicable to any future large aerospace development.

In each of the above domains, reusable launchers are pushing the demands for advances far beyond other conventional applications. It can, therefore, be expected that even a partial achievement of the goals set for these launchers will yield important benefits for future aerospace vehicles.

All of the technologies developed for reusable launchers that support hypersonic flight in the atmosphere (air-breathing propulsion, thermal protections, aerothermodynamics) will help the potential development of high-speed military aircraft (in the high supersonic to hypersonic range). The hypersonic speed capability could become an important asset in the future, if the progress made on detection means are faster than the progress made on low-observability.

ANNEX 7: PROTECTION AGAINST LASERS AFFECTING HUMAN VISION

Introduction

This annex amplifies material contained in Chapters 5 and 6. It contains an unclassified compilation drawn from existing (classified) documents and personnel communications.

Laser Threat

A couple of common characteristics associated with a laser source are its monochromicity and its brightness. However, lasers that can simultaneously operate at more than one wavelength are available. Alternatively, there are lasers which can be tuned to new wavelengths from shot to shot, and some types can have their wavelength changed rapidly during an output pulse (chirping). If any of these systems were to operate at visible wavelengths it would be difficult to provide good protection whilst maintaining good visual function, as the protection goggles would absorb most or all visible light. Two types can be considered:

- Tuneable or frequency agile lasers; the wavelength can be changed dynamically over a small part of the electromagnetic spectrum;
- Frequency diverse lasers, the wavelength can be selected, changing from one part of the spectrum to another.

The importance of frequency agile lasers and wavelength diverse lasers is that it is not easy to block their emissions with fixed wavelength filters, hence, making protection measures is very difficult, particularly if the range of emission wavelengths is unknown.

Some Important Lasers

Nd - YAG lasers (wavelength 1060 nm) are the most deployed lasers; they are being used for range-finding and target designation. These are single-frequency lasers; however, the operating frequency can be doubled (wavelength 532 nm) so that the emission is in the visible part of the spectrum.

Tuneable solid-state lasers are the alexandrite laser (700 - 830 nm) and the titanium-sapphire laser (660 - 1060 nm). Frequency doubling and Raman shifting can convert the output to wavelengths within the visible part of the spectrum.

Another form of laser that has an output that can occur over a range of wavelengths is a dye laser. In this case, the active medium contains organic dye molecules dissolved in a suitable solvent. This type of laser may be excited by another laser or by energy from a flashlamp. Flashlamp-pumped dye lasers can be very compact. The range of wavelengths over which this type of laser can be tuned is usually small, often on the order of about 10 nm. Another important aspect of dye laser sources is wavelength diversity. The wavelength of emission can be changed from one part of the spectrum to another by merely changing the organic dye used in the gain medium. This type of laser is most efficient in the visible and near infra-red part of the spectrum. Flashlamp-pumped dye lasers are capable of operating at high-average power, producing high brightness beams that can deliver significant energy densities at ranges of several kilometres. Additionally, this type of laser is capable of emitting several wavelengths simultaneously.

Effects of Laser Radiation

The intensity of the laser light, combined with its directionality, means that there is the potential to dazzle or damage sensors at significant ranges. Amongst the most sensitive sensors which are vulnerable to laser light is the human eye. The special vulnerability of sensors is associated with the way in which they concentrate incoming energy, by focusing it onto radiation-sensitive material. Wavelengths to which the sensor is sensitive, so called 'in-band' wavelengths, are concentrated in this fashion. In the case of the human eye, visible light is focused onto the retina by the optics of the eye. The flux at the retina may be as high as 105 times the flux at the cornea. The range of wavelengths that are focused and transmitted through the ocular media are called the Retinal Hazard Region, and extend from 400 nm to 1400 nm. Wavelengths that are 'out of band' to a sensor may be absorbed at the front surface of the sensor, but can usually be filtered out by an appropriately damage-resistant material.

The direct effect of laser light striking a sensor will take one or both of two forms. The light may cause glare[1] which renders the sensor ineffective, or it may damage the sensor. Glare is essentially a result of scattering of the light, both in the optical media through which it passes (atmosphere, transparencies, optics), and in the eye itself. The characteristics of scatter within the eye are known. Measurements of light scattering in the atmosphere have been carried out, and measurements of any other optical elements may need to be carried out before the degree of glare in a particular scenario can be predicted. Following glare, there is a period of recovery, sometimes referred to as flash blindness. Together, glare and its after-effect, constitute dazzle. The extent to which glare affects the performance of a visually mediated task depends on a range of environmental and task factors, an important one of which is the ambient light level. At low-light levels, the extent of glare and the duration of the after-effects are increased. At the high levels, which may be obtained during daylight aircraft operations, dazzle that might disrupt visual tasks will not be achieved without energy levels that might cause damage to the eye.

The mechanisms and consequences of eye damage depend on the wavelength and energy of the light reaching the eye. The wavelength determines which structures absorb the energy. Medium to long-visible band wavelengths, at energies of around 1mJ, will result in a temperature elevation at the retina sufficient to cause a thermal lesion. Studies have shown that in order to disrupt the performance of visually mediated tasks, thermal lesions would have to cover a larger area of the visual field, located near the centre of the retina. At higher intra-ocular energies, and favoured by extremely short-pulsed sources, disruption of retinal structures increases in likelihood.

The conditions of dazzle and thermal injury are known. The ability to predict the size of a thermal lesion is at present rudimentary. The threshold for the various types of retinal haemorrhage is rather variable, known with less certainty, and data are relatively scarce. The realistic threshold for causing mission defeat in a highly motivated and trained pilot is not known.

[1] Definitions of specialised terms are listed at the end of this Annex.

Description of Some Effects

Pilot vision may operate at less than optimal in a variety of circumstances. In addition to the possible impairment caused by solar glare from the canopy or poor instrument contrast, a more serious threat to pilot vision may be posed by laser weapons. A number of effects may be seen. A direct consequence of the incidence of laser radiation on the eye is termed veiling glare. This refers to a luminous veiling haze (or dazzle) that surrounds any bright light source and is likely to obscure objects imaged onto adjacent retinal receptors. This dazzle is derived from two principal sources: first, there is significant scatter of light within the tissues of the eye; second, additional optical spread may be attributed to atmospheric effects. Whereas ocular spread is relatively quantifiable, atmospheric spread is more difficult to define, as it is dependent on a large number of meteorological variables.

After the offset of a laser source, an observer is likely to experience some residual after-effects, the severity of which are related to the energy absorbed at the eye. At lower energy levels, the observer is likely to experience a temporary elevation of contrast thresholds across the retina, caused by the exposure of the eye to an intensity of illumination far in excess of that to which it is currently adapted. This is often referred to as flash blindness, and recovery is dependent on adaptation state and the intensity of the incident light. The effects are, however, likely to persist for a significant time after exposure (up to 100 seconds).

Another after-effect, often confused with flash blindness, is "after-image". After-images are the perception of light, dark, or coloured spots after exposure to a bright light. After-images may persist for minutes, hours or days. After-images are very dynamic and can change in colour and intensity, depending upon the background being viewed. It is difficult to correlate the colours of after-images with specific wavelengths. After-images are often annoying and distracting, but they are unlikely to cause a visual decrement.

Higher energies of incident radiation may cause actual retinal damage. A typical result of such exposure is the formation of an additional blind spot, or scotoma, within the irradiated area. The likelihood of recovery from such damage is related to the mechanism by which it was caused. For instance, physical damage to the surface of the retina caused by the heating effect of light

near the infra-red is likely to be permanent, whereas there exists a good chance of recovery from photochemical damage caused by light near the blue end of the spectrum. Recovery, in either case, occurs over a long timescale, and the scotomata created are likely to interfere with visual processes for a considerable period.

Laser weapons are, therefore, likely to cause two types of visual disruption. First, during laser exposures the observer is dazzled and immediately after exposures experiences a degree of flash blindness, which has a similar effect to dazzle and decays with time. Second, in certain configurations, a laser may cause ocular damage, forming additional blind spots (or scotomata) on the retina. The blind reflex is designed to protect the eye from exposure to potentially hazardous light energies but occurs over approximately 0.25 sec and may, therefore, be too slow to prevent damage by intense laser radiation.

Some Consequences

Dazzle. It has been demonstrated in a series of experiments that a dazzle source may cause a significant decrement in tracking performance. During irradiation, dazzle effects may hinder target acquisition and tracking. The precise degree of impairment is likely to be a function of the intensity of the dazzle source, the proximity of the dazzle source to the target, and the contrast of the target. In the study, it was shown that maximum interference to tracking occurred when target and dazzle were coincident. A significant impairment to tracking was evident for target-dazzle offsets of 2° and 3°, even though the target was visible through the dazzle halo at this offset. It has also been demonstrated that tracking performance is likely to be impaired after the offset of a laser or other bright light source.

Temporary Scotoma. Experiments suggest that even small scotomas could have a significant import on visual performance in the cockpit. Laser flashes produce increase in target acquisition time under all contrast and background conditions. Increases range from 2 to 12 times the baseline acquisition scores in the test conditions. The effects are greater for targets that are more difficult to detect.

Protection and Hardening

A variety of methods have been proposed or implemented to protect sensors and eyes against lasers. These include narrow-band spectral filters, complementary filters, fast optical switches, non-linear optical materials, and indirect viewing. Each method has disadvantages, and the ideal solution has yet to be developed. Narrow-band filters do not exclude all possible threat wavelengths and may affect vision, particularly at low-light levels. The wavelength specificity of some filters is angular dependent, so they are more appropriate for helmet than canopy mounting. As a result of the proximity of head-up display (HUD) phosphor and some laser-dominant wavelengths, these filters tend to interfere with HUD visibility. The complementary filter solution is a form of indirect viewing that allows light of selected wavelengths to enter the cockpit, but not the eyes. A sensor (such as night vision equipment (NVE)) that is sensitive to one waveband, but displays another, is used between the filter elements.

Optical switches that respond sufficiently, in terms of speed and optical density to exclude the first of a train of laser pulses, have been demonstrated in the focal place of electro-optical sensors, but do not exist in a form which can protect the eye alone. Improved optical switch materials, while desirable, may not preserve useful vision when activated.

Non-linear optical devices provide the possibility of transmitting normal light, while attenuating hazardous energy. Indirect viewing using a TV system achieves this purpose, but appropriate optical solutions would be extremely desirable for the protection of sensors as well as eyes.

The cost of each option, in terms of its impact on normal visual function, and the interaction with light level and cockpit displays, can be assessed using existing techniques. Conditions under which narrow and broadband filters may afford protection and aid normal visual function have been identified.

If a satisfactory level of protection cannot be attained, it may be necessary to introduce the closeable or closed cockpit. Studies on the implications of this option have started.

The aim of <u>protection</u> is to prevent laser light from arriving at the sensor. The aim of <u>hardening</u> is to minimise the effect of sensor irradiation.

There is a distinction between passive-protection devices and active-protection devices. The optical properties of <u>active</u>-protection devices are

irradiance dependent; switches belong to this category.

In passive devices, there is no radiation-dependent modification of the optical properties of the device; examples are absorption- and rejection-fixed wavelength filters. This type of device is best suited for protection against a few known fixed-wavelength lasers. Characteristics are the relative low cost and incorporate the utilisation of established technology.

Another distinction is between in-band and out-of-band devices. Protection that prevents illumination from acting on the sensor, in a wavelength band where the sensor would otherwise provide a signal, is called "in-band" protection. Conversely, protection of a detector in a wavelength band where absorption occurs, and thus damage is feasible, but the detector is not able to provide a signal, is called "out-of-band" protection.

To appreciate this point more clearly, consider the eye. In normal daylight conditions the retina is sensitive, that is, it is able to convert optical information into electrical impulses, over a wavelength range of 380 nm to 750 nm. However, tissue in the retina can absorb radiation at 1000 nm, but it does not provide an electrical output. A component that prevents light in the band 380 nm to 750 nm from entering the eye is in-band protection, and a component preventing the 1000 nm radiation from entering the eye is out-of-band protection.

Specifications for protective devices include the following concepts:

- If the incident radiation intensity is I_0 and the transmitted intensity is I_t, then the transmission is given by

  $$T = I_t/I_0.$$

- In general this transmission is strongly wavelength dependant:

  $$T = T(\lambda).$$

- The optical Density (OD) of the device is defined by

  $$OD = -\log T$$

  so, an optical density OD = 4 means a transmission $T = 10^{-4}$.

In-band protection devices decrease the amount of radiation falling onto the detector. The sensitivity of the sensor system, integrated over the wavelength range, is therefore smaller. This is reflected in the concept of the integrated detector response (IDR).

Protective devices must reduce the transmission at laser wavelengths (in general an OD of 4 or greater is required) while at the same time keep the IDR above a minimum required level.

Unique to the eye is the property that the retina has two response curves, one for the rods and one for the cones, which are displaced in wavelength with respect to one another. This results in two IDR factors for the eye, the scotopic IDR and the photopic IDR, applicable to night and day vision respectively.

Five general areas of technology will be reviewed as possible passive in-band protective components:

- Absorption over wide wavelength range in neutral density filters;
- Absorption in coloured glasses due to inorganic semiconductor inclusions;
- Absorption by organic dyes in liquid or plastic hosts;
- Interference reflection in multilayer structures fabricated from isotropic inorganic (or organic) materials: Quarter-wave Reflection Stacks, Bragg Reflectors, and Rugate Reflectors;
- Interference reflection in holographic rugates.

Passive Protection

Neutral Density Filters. These filters offer a wide wavelength range absorption. The OD is essentially independent of wavelength, and therefore the device reduces the IDR considerably. This method of protection can only be used during the day (if at all).

Coloured Glasses. The absorption is caused by inorganic semiconductors. Most of these filters are edge filters; the transmission is reduced below a certain wavelength. In some circumstances semiconductor-doped glasses can be manufactured to provide band rejection

properties, but the rejected band is rather broad. In general then, coloured glass filters provide cheap, off-the-shelf protection in and around the visible region of the spectrum, either as band rejection filters or as edge filters. Although they retain their protection properties at non-normal angles of incidence, they cause dramatic reductions in IDR in the visible band because of the broad wavelength absorption features, and they are difficult to custom make for a given requirement.

Organic Dyes Absorption. These devices are the organic analogue of the semiconductor-doped glass filters mentioned in the previous section.

Absorption Filters (general). Although these fixed-wavelength absorption filters have the advantage that they can operate effectively over all angles of incident light, they remain unsuitable for applications involving multi-line protection, simply because of the width of the absorption bands, and hence the drop in the IDR. The (scotopic) transmission for any absorption device will be a function of the number of laser lines attenuated in the visible part of the spectrum, hence, they form no solution for night use.

Interference Reflection in Multilayer Structures. In its simplest form, this technology is relatively mature, having been practised for 50 years or more, although its origins are much older. Traditionally, reflection filters have been grown using inorganic materials in vacuum deposition equipment; recent years have seen the rapid development of deposition methods that allow multilayer interference structures to be fabricated out of organised layers of organic molecules. In simple geometries, the range of wavelengths reflected will be relatively broad and not all of the preferred wavelengths will be reflected, a large portion are transmitted. Improving the situation requires a greater sophistication.

Three types of interference filters can be considered: Quarter-Wave Reflection Stacks, Bragg Reflector, and Rugates.

<u>Quarter-Wave Reflection Stacks.</u> Enhanced reflection properties can be achieved if the radiation enters a second thin film that is of a different refractive index, yet provides an equivalent optical path length to the first film. In this way, more of the preferred wavelength is removed from the transmitted light and is reflected. Building up a multilayered structure of iterating high and low refractive index media in this way, each of an optical thickness of a quarter wavelength, results in the well-known quarter-wave interference stack. The basic properties of this interference structure are analogous to all other types of interference structure.

Problems with it are basically fourfold. Constructing very narrow reflection bands involves evaporating many layers, resulting in thick structures. Growth techniques to achieve this have only recently been developed, with the introduction of ultra-high vacuum methods and detailed growth control. Stress generated in the films, and impurities in the materials evaporated using conventional vacuum deposition methods, results in unstable films which crack and disintegrate. These problems are now largely solved. Because the structure relies on constructive multiple reflections, only one reflection band can be optimised in a given structure. Without growing two independent quarter-wave stacks and using them in series, two arbitrarily chosen reflection bands cannot be rejected at one time. This tandem arrangement can lead to transmission problems and is a drawback, from the point of view of maintaining a high IDR. The final problem with the quarter-wave stack structure is its relatively low laser-induced damage threshold (LIDT). Interface lattice mismatches, defects, and impurities are in abundance, which leads to absorption processes and thus heat which can result in damage to the multilayered structure. An improvement in damage threshold, and to some extent an enhancement in reflection properties, can be gained by going to the technologically more demanding Bragg Reflector structure.

<u>Bragg Reflector.</u> There are many similarities between quarter-wave reflection structures and Bragg reflections. Both are constructed from alternating high and low refractive index layers, using mostly, but not always, ultra-high vacuum methods, and both have the limitation that the centre wavelength of the designed band is sensitive to the angle of the incident light. However, the advantage of Bragg reflectors is an improvement in the laser-induced damage threshold. This advantage has to be offset against the more demanding fabrication tolerances of the Bragg structure.

<u>Rugate Interference Structure.</u> Generating a series of unwanted sidebands and higher harmonic principle reflection bands is an unfavourable

attribute of the interference structures so far considered, because of the implication for IDR. In each of the structures, the thickness of the layers was designed to add, constructively, reflections from the multiple interfaces for a given wavelength. Clearly, a range of reflections will be generated of different strengths for all incident wavelengths. The result of this complicated set of partial reflections and partial phase-matching is the sidebands of the interference structure and the higher harmonic principle reflection bands. In the rugate, the structure departs from a series of discrete refractive index discontinuities and uses a smoothly varying refractive index profile. In order to achieve the ultimate goal of a single wavelength band, which is narrow in wavelength spread and does not have associated with it a series of sidebands to compromise the IDR, it is necessary to modify the oscillating refractive index profile with an amplitude modulation. Theoretically, it is now possible to fabricate complicated filter responses with optimum IDR, using a rugate method. However, the fabrication procedure for such complex structures is very difficult.

Holographic Filters. Basically, a holographic filter is similar to the previously described rugate, in that it is a structure composed of a sinusoidal varying refractive index profile. However, the method of fabrication is quite different.

In exactly the same way as all of the other interference filters discussed, the holographic filter reflection band is a function of the angle of the incident light. Altering the angle of the incident light moves the reflection band to shorter wavelengths. The spectral width of the reflection band depends on the hologram thickness and also the modulation of the sinusoidally varying refractive index profile.

Improving the angle of view of fixed wavelength interference and holographic filters can be achieved by fabricating the structure onto a curved surface. In practice, a curved filter does not provide complete protection to all angles of incidence, because of the finite size of the eye pupil. Clearly, this is going to involve a more difficult manufacturing process.

Active Protection.

The ideal active transient protection device allows all wavelengths in the sensors bandwidth to reach the sensor for normal irradiance levels, but for high levels, such as those originating from lasers, optical limiting occurs and protects the sensor from damage or dazzle. Optical limiters are the protection devices offering the greatest possibilities against tuneable frequency lasers.

With specification conflicts for in-band protection - that not only must the IDR be high, but that the provided OD must also be high - and the need to guard against ever-increasing numbers of threat wavelengths; the need for transient protection emerges.

The transient protection options for in-band protection are self-activated switches, and externally activated switches.

Self-Activated Switches. An ideal device is one in which the transmitted energy increases with increasing input energy, up until a certain threshold energy whereupon the transmitted energy is cut off. Equally, a component could as well be protected if, at some input energy threshold, the output energy remains fixed; this type of device is referred to as a limiter. In reality, many of the considered effects behave in a non-ideal fashion and only partially limit.

To drive a physical system into a non-linear optical regime, the incident energy density typically has to be high; and, hence, in order to utilise non-linear optical mechanisms in self-activated switches, the device must be placed at an intermediate focal plane (IFP). So far, all considered self-activated switches are IFP devices, but with a new class of material, with much larger optical non-linearities, the possibility of the self-activated switch being a lens coating, for example, exists.

There are three important parameters associated with all self-activated switches. The most important is the threshold at which a switching or limiting occurs. Second most important is the output maximum, and third is the dynamic range of the device, which is defined as the difference in input energy between the threshold and the material damage level. All of these parameters are material dependent; but within a particular optical system there is some scope for modifying the optical systems threshold, maximum throughput, and dynamic range by altering the optical design.

The physical mechanisms that can be considered are the following:

- Gas breakdown (a broadband effect, that is a whole range of wavelengths can

trigger the mechanism, providing protection in the visible and infra-red);

- Metal semiconductor transitions (a broadband effect, providing infra-red protection);
- Organic photophysical changes (a less broadband effect providing visible protection);
- Induced scattering e.g., within a carbon black suspension (a broadband effect, providing visible and infra-red protection);
- Total internal reflection (a less broadband effect, with angle sensitivity, providing visible and infra-red protection);
- Two-photon absorption and self-defocusing (a broadband effect, providing visible and infra-red protection);
- Photorefractive effect (a broadband effect).

Externally Activated Shutters. In any externally activated shutter there must be some form of detection system to alert the system that protective action is necessary; often this detection system is referred to as a "laser-warning receiver" (LWR). Either the intensity of the incident laser light can be monitored, or the intensity and wavelength can be monitored, depending on the type of shutter to be activated. There are two basic options:

- Activation of a totally opaque shutter. In this case, no wavelength measurement is necessary, just intensity. The IDR = 0 for the duration of the shutter activation. If the threat laser is a system which has a low duty cycle, that is its "on" time is small compared to its "off" time, this type of shutter may be acceptable. If, however, the threat laser has a high duty cycle, or is CW, unacceptable obscuration of the detector results and the task of the threat laser has been achieved. Totally opaque shutters have the advantage of being relatively simple, and cost effective, but are of only specialised applicability;
- Spectrally selective shutters. Here the requirement that the LWR is able to interrogate the laser wavelength is necessary. This can be achieved, in simple terms, with a dispersive element in the system. Although more complex than the totally opaque shutters, they are able to maintain high IDR throughout the laser threat and can counter an agile laser threat. Some of these devices are tuneable interference filters.

Within these two classes of shutter, various mechanisms can be utilised to provide a shutter effect. The options are:

- Mechanical shutters,
- Magneto-optic shutters,
- Electro-optic shutters,
- Acousto-optic shutters.

Hardening

So far in this section, the ways in which a detector might be protected, by introducing passive or active components within the optical path, have been considered. In each, the aim has been to stop the light from arriving at the sensor. If the protection fails and the light is falling onto the detector, damage can occur.

Concepts exist to modify the operation and design of the optical system to make it less susceptible to damage by laser attack. This is more a hardening option. To begin with, all new optical systems should be designed to incorporate an intermediate focal plane (IFP), thus allowing for a switching element to be introduced.

Another hardening option is to use image processing to reduce unwanted effects of the radiation, e.g., contrast enhancement.

Furthermore, the detector itself could be hardened. Only small amounts of information are available in the literature. Due to their operating principle and design, staring-array detectors are more susceptible to laser damage than scanning systems. With staring systems, the laser energy remains incident on the detector continuously. Whereas, with a scanning system, the laser energy only arrives at the detector when the scanning optic is orientated towards the laser source. Hardening of the system might then be thought of as a movement away from staring-array systems.

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DEFINITIONS

glare:	relatively bright light, or the dazzling sensation of relatively bright light, which produces unpleasantness or discomfort, or which interferes with optimal vision.
dazzle:	to obscure or confuse vision by exposure to excessive or extraneous light.
flash blindness:	visual loss during and following exposure to a light flash of extremely high intensity.
scotoma:	isolated area of absent vision or depressed sensitivity in the visual field.

ANNEX 8: THE FUTURE OF AIRCRAFT GAS TURBINE ENGINES

Introduction

As we look well into the next century, there is still no foreseeable substitute for the fire power and mobility of aircraft and rotorcraft, and there is still no substitute on the horizon for gas turbine engines as the primary propulsion system. In addition, NATO is on the threshold of new weapon system capability enabled by advanced turbine engines - in the very near term the technologies are in place for Advanced Short Take-Off/Vertical Landing (ASTOVL) and sustained supersonic cruise; and in the far term the potential exists for advanced Unmanned Aerial Vehicles (UAVs), global reach transports, global strike bombers, and rapid reaction fighters. In addition, excess engine power will enable future "electric" directed-energy weapons and new non-hydraulic, non-mechanical aircraft control capability.

Initial thinking of "future propulsion" started in the United States (US) with the Integrated High-Performance Turbine Engine Technology (IHPTET) program. It was established in 1985 to be the first joint US Air Force, US Navy, US Army, ARPA, NASA, and industry program focused to develop turbine engine technologies for more affordable, more durable, higher performance propulsion engines. Major work by the entire US propulsion community made it happen.

Due to its visionary planning, quantified goals, and significant broad-base payoff, IHPTET is now the model programme for the world and is the keystone for future military and civil propulsion. Its merits are well understood. In the United Kingdom (UK) and France, major effort is underway to formalise similar national programmes. The UKs Advanced Core for Military Engines (ACME) and the UK/France effort for Advanced Military Engine Technology (AMET) are leading the way forward for Europe. In addition, in Europe, considerable advanced research focused on engine improvements is underway, to various degrees, by almost all other NATO Nations. These nationalised programmes are forming the springboard for propulsion advancements for NATO's airborne warfighters of the next century. NATO, with this new propulsion capability, will enjoy full air superiority in all emergency situations.

Aircraft Gas Turbine Engine Impact

The momentum of the current work on gas turbine propulsion technology must continue through the next few decades and concentrate on fully developing the emerging technologies if NATO is to achieve total success in the future. This technology will not only improve on our current capability, but it will ensure NATO's technical dominance in aerospace development. Through solidly investing in the formulation of turbine engine innovative concepts, success will happen.

These innovative concepts (technologies) are key to enabling future military aircraft capabilities, and they have significant impact on defence costs. The propulsion system (engine plus aircraft fuel) typically accounts for 40% to 60% of the take-off gross weight for both current and future aircraft (Figure 1 on the following page), and about 20% to 40% of aircraft/weapon system Life-Cycle Costs (LCC) - development, production, maintenance, operations, and support costs. Accordingly, any increase in engine performance and reduction in engine costs, associated with established aggressive propulsion system goals, will be a major contributor to achieving significant gains in upgraded and future NATO air platforms. This major focus by the NATO turbine engine community will not only advance NATO aircraft superiority through high-performance, affordable, robust engines, but will improve many aspects of commercial aviation. Up to 80% of all military propulsion is usable for civil aerospace, marine, industrial, or ground power industries.

The broad-base aircraft mission enhancing payoffs from this advanced NATO research are:

- Major extensions in operational range;
- Reductions in gross weight and acquisition costs for new aircraft;
- Increased speed to intercept the enemy or to reach the target faster;

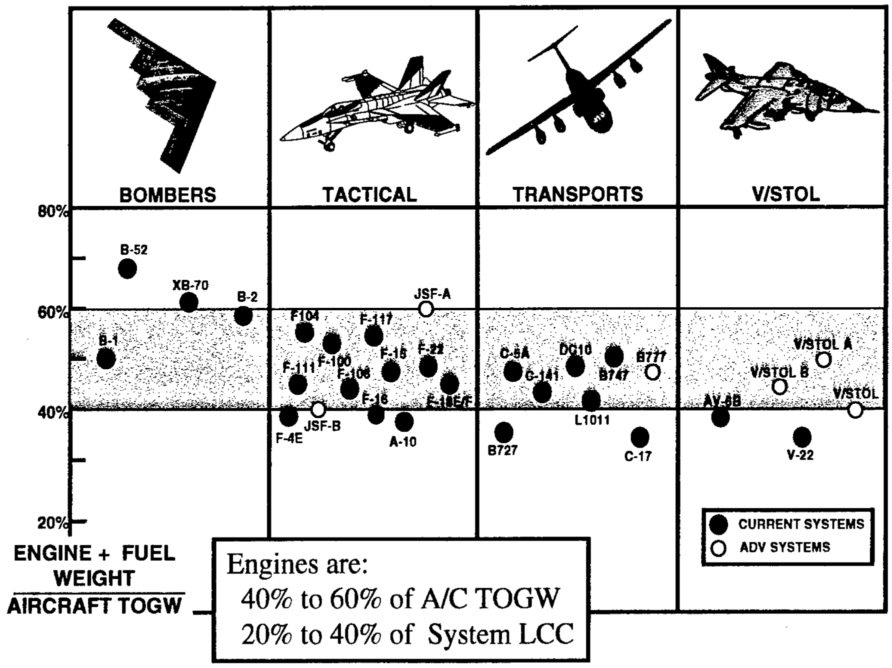


Figure 1: Turbine Engine Technology Impact

- Increased quantity of weapons brought to the target;
- Overall platform improvements by closely integrating the rapidly advancing more electric propulsion systems and airframe electronic flight control systems;
- Enhanced combat survivability, through performance gains and improved low-observable technologies;
- An ASTOVL aircraft with greater range and payload capability than an equivalent-size current fighter.

Examples of the benefits of technology application include the implementation of longer range, multi-mission fighter/attack aircraft such as the new F-22, F/A-18 E/F, the Eurofighter 2000, the Dassault Rafale, and the Joint Strike Fighter (JSF), which will allow one type of aircraft to conduct bombing operations while successfully defending itself against enemy aircraft. More fuel-efficient engines for helicopters and surveillance aircraft will allow them to conduct anti-tank and anti-submarine warfare operations for longer periods of time and at greater ranges. Long-range cruise missiles, laser-guided weapons, and other type missiles will be used to attack hardened or heavily defended targets of high capital value, with improved kill ratios and less collateral damage, while reducing the exposure of aircraft and pilots. In a like manner, the role of UAVs will increase at a significant rate. They will fly the most dangerous missions, be able to stay aloft for weeks or months at a time, and be inexpensive and durable. These UAVs will give the battlefield commander major options - options not yet fully realised in the most advanced doctrine and battlefield scenarios. All of this advanced aircraft capability will "fly" using the newly emerging, high-performance, low-cost gas turbine engine technology.

Development of Gas Turbine Engine Technology Needs

Many major technical barriers must be successfully challenged for the payoffs discussed above to be achieved. These barriers include:

- Increasing component efficiencies,
- Advancing structural integrity,
- Increasing aerothermodynamic design capability (and control of heat transfer),
- Improving combustion stability over a broad operating range with minimal emissions,

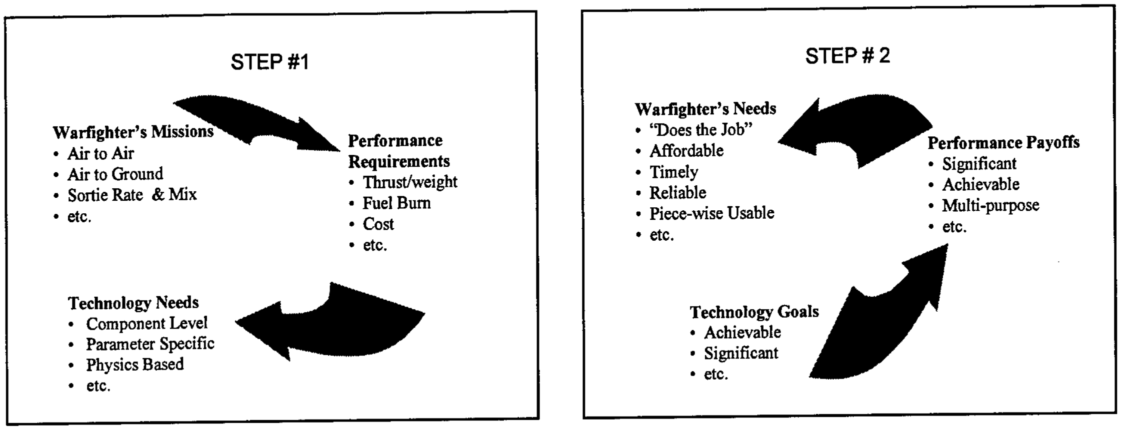


Figure 2: Propulsion System Technology Planning Process

- Developing high-quality, low-cost materials of lower density and greater high-temperature strength,
- Maturing innovative structural design concepts,
- Ensuring compatibility of these developments with affordable manufacturing and repair processes.

A key ingredient of the technology development cycle to overcome these barriers is the utilisation of bench, rig, and full-technology demonstrator engines, where integrated component behaviour is evaluated in a realistic environment. Through this proper testing, a high degree of technology readiness and transition potential will be understood and validated.

Currently, gas turbine engines power the total variety of fighter/attack, heavy transport/patrol type aircraft and helicopters, in addition to UAVs and several missile systems. Each of these weapon systems had to be developed with both a primary mission, as well as other multi-role considerations that are integral to overall military operational plans. A prevailing issue with the gas turbine engine "cycle" is the need for increased power combined with lower fuel consumption. These are opposing requirements with respect to the thermodynamics of the cycle. In order to overcome this dichotomy, interactive sub-system design philosophies using the best technology are required, in order to provide a "balanced performance" necessary to meet all aspects of the mission requirements. The process used by the gas turbine engine technology planners to meet all the aircraft roles is shown in the two-step process of Figure 2. In Step 1, the "warfighter's missions" drive the "performance requirements," which in turn set the "technology needs". In Step 2, the technology needs that were defined in Step 1 are developed into meaningful "technology goals". These goals are then evaluated for their contribution to achieving "performance payoff". These payoffs are then evaluated relative to what they provide the warfighter in terms of enhanced capability - usually much greater capability and more diverse capability than was first envisioned. Each of the technologies under development, for example in IHPTET and beyond IHPTET, have been chosen by application of this process.

Through the application of the process shown in Figure 2, the path to this advanced, multipurpose propulsion system capability of the future is well described. It is well-based in physics, but it will take high-quality, focused effort to achieve. This path includes:

- Higher temperatures at combustion initiation to increase thermal efficiency (or decrease specific fuel consumption), with expanded flight envelope performance;

- Higher maximum temperatures to increase the thrust (work output) per unit airflow;

- Less weight per unit airflow to increase the work output per unit weight (thrust/weight or power/weight ratio).

All of these advancements must be accomplished with increased internal component efficiency, durability, and life, while decreasing cost. Specific technology development areas include:

- Increased aerothermodynamic design capability for improved component efficiency levels and control of heat transfer;

Progress in All Three Areas Is Required for Success!

ADVANCED AERO/THERMAL + NEW MATERIALS + INNOVATIVE DESIGNS

ADVANCED AERO/THERMAL

- 3-D Viscous CFD Tools
- Swept Airfoils
- Stoichiometric Combustors
- Advanced Turbine Cooling
- High Stage Loading Compressors
- Short Exhaust Nozzles
- Variable Cycle Concepts
- Vaneless LP Turbines

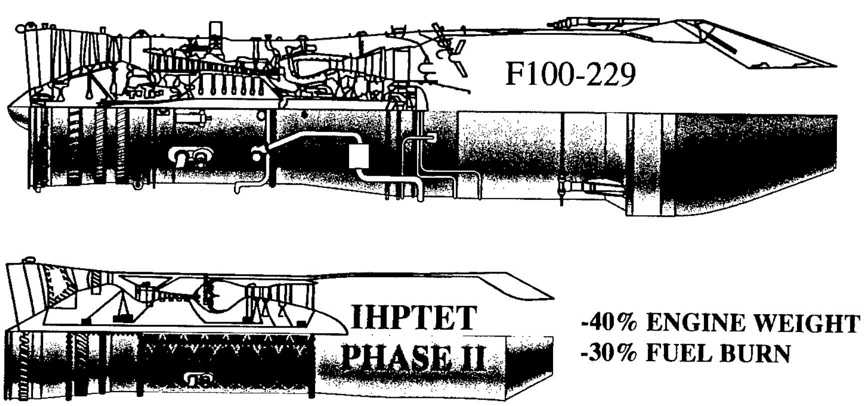
NEW MATERIALS

- Lightweight Composites
  - Metal Matrix
  - Carbon Based
  - Ceramic Matrix
- Ti & Ni Aluminides
- High Temp Al & Ti
- High Temp Non-structural

INNOVATIVE DESIGNS

- Fiber Reinforced Hardware
  - Ring Rotors
  - Blades
  - Static Structure
- Multi-use Structure
- Simplified Rotor Supports
- Integral Blading
- Laminated Structure
- Endothermic Fuels
- Magnetic Bearings

Figure 3: Propulsion Technology Triad



-40% ENGINE WEIGHT
-30% FUEL BURN

LOWER ACQUISITION COST

-20% @ SAME THRUST

-40% @ SAME MISSION

Figure 4: Revolutionary Advancement in Turbine Engine Design

- Higher temperature and lower density materials;
- Innovative structural concepts;
- Robust designs that allow the engine to accommodate changing mission requirements while maintaining a high degree of readiness;
- Durable designs and structures to provide full system life;
- Maintainability concepts, such as modular construction and minimisation of support equipment.

All of these developments must be compatible with affordable manufacturing processes and be accomplished in an integrated manner for each of the major component areas, and for engine configurations as a whole. Advancement in total propulsion capability is a synergism of the three technology areas shown in Figure 3 - success in one area alone will not do the job!

Today's (and tomorrow's) economic situation demands more affordable and durable propulsion systems. All aspects that impact the total system life-cycle cost (LCC) can be improved with the successful application of advanced technologies. The technological range is very wide - from enhanced computational fluid dynamics (CFD) techniques that enable designers to achieve the final design more rapidly, reduce the amount of "cut-and-try" testing and in general reduce the development time and cost through improved manufacturing techniques to produce the systems - to the reduction in the number of parts, elimination of certain systems (for example, replacement of large portions of the lubrication system with magnetic or ceramic bearings), integrated diagnostics systems, and more fuel-efficient power plants that reduce the operational and support costs.

For example, studies in the IHPTET program have quantified the weight and size influence on cost for both a new engine in a fixed airframe and a new engine in a new airframe. Using IHPTET Phase II (planned 1997 demonstration date) technologies for example, studies show a 40% acquisition cost savings for a system with a constant aircraft thrust loading and fuel weight fraction equivalent to an F-16. Using Phase II technology to retrofit a new engine to a current airframe (new engine at same thrust) shows a 25% acquisition cost savings. The benefits of the technology on the engine size and weight are shown in Figure 4. Using IHPTET Phase II technologies individually or in small upgrade packages, for modernisation of current propulsion systems, show proportionate values of LCC savings. Considering that the US Government spends approximately $15 billion per year on aircraft and missile gas turbine propulsion systems, a 25% to 40% acquisition cost savings amounts to a significant financial savings. For Phase III technologies (planned 2003 demonstration date) and "Beyond IHPTET" planning (2009 demonstration date), the payoffs increase to a 50% to 60% cost savings.

In the future, each aircraft/rotorcraft will require an engine that satisfies a specific range of performance and cost goals. To meet these goals the engine manufacturers (or consortia/teams) must determine what technologies are to be applied and how each technology is to be traded-off to maximise the effectiveness of the total weapon system. A fully equipped technology base with multi-use application is the key to successful propulsion system development and production.

This concept is shown in Figures 5 and 6 (following page). Figure 5 shows the broad technical aspects of the "common core" technology base - all currently in the engine technology development plans. Figure 6 shows the diverse capability that could be achieved with revolutionary turbine engine technology providing dramatic gains in range, reduction in mission time-to-target, and reaction time - all achievable through advancement in propulsion technology.

Turbofan/Turbojet Propulsion Technology Needs

The advanced strike aircraft and rapid-reaction fighters, as shown in Figure 6, in general have certain system requirements:

- Multi-Mission Flexibility,
- Minimum Vehicle Size and Weight,
- High-Combat Manoeuvrability,
- Low Fuel Burn,
- Dry Supersonic Operation,
- Affordable Cost,
- Supersonic Acceleration and Turn Capability,
- Easy Maintenance and Repair.

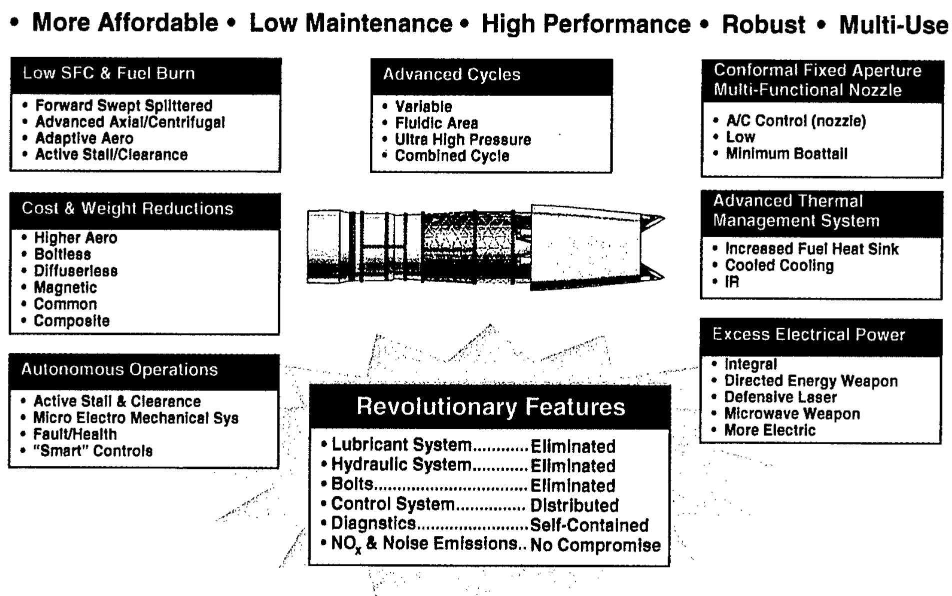


Figure 5: Emerging Advanced Techniques

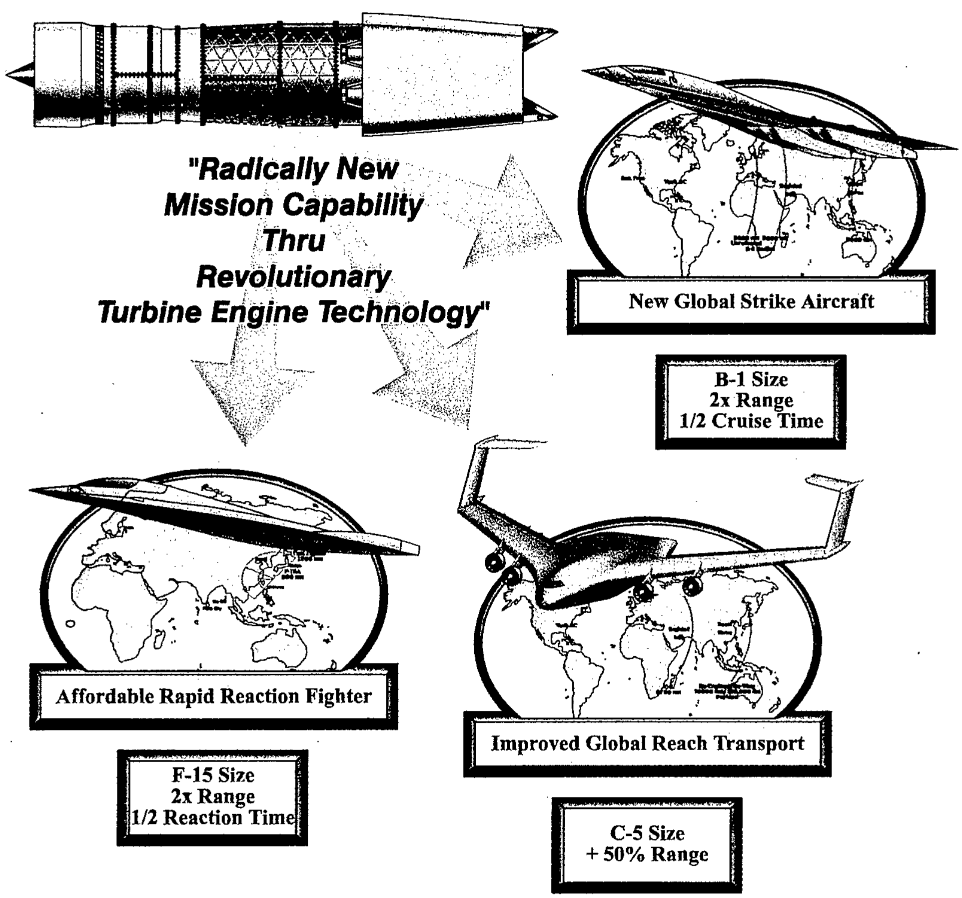


Figure 6: New Capabilities Through Advanced Propulsion

The fighter aircraft shown in Figure 6 have common attributes that are satisfied by propulsion systems having many of the emerging technologies outlined in Figure 5. These fighter engines typically are mixed-flow afterburning turbofan engines (bypass ratios of 0.2 to 1.0) which provide high vehicle airspeed (high-thrust) and high values of "excess specific power" - the agility advantage. These engines are comprised of technologies which, when focused, will achieve:

- High Thrust-to-Weight Ratio,
- High Specific Thrust Cycle (Thrust/Airflow),
- Low Specific Weight (Weight/Airflow),
- Low Specific Fuel Consumption (Fuel Flow/Thrust),
- Low Life-Cycle Cost - total cost of ownership,
- Increased Values of Signature Reduction.

Fighter pilots are convinced that "speed is life, and life is speed". The higher speed is necessary for both ingress to, and egress from, the battle area, and for the ability to quickly recover lost airspeed due to combat manoeuvring.

Another benefit of higher thrust levels is improved payload capability, which is very important for attack type aircraft as they apply ordnance-on-target. The major key to higher specific thrust is higher operating temperatures internal to the engine. Current combustor and turbine systems still operate well below the stoichiometric chemical limits of kerosene-based fuels. In the future, major increases to these values will be required. For this to be achieved, new, high-temperature, non-metallic materials are a major emphasis of new designs in the compression systems. In the hot section (combustor, turbine, nozzle), advanced materials need to be integrated with thermal barrier coatings and innovative cooling techniques that require design in order to be an effective improvement to the engine cycle. The other factor of the thrust/weight equation is lower engine weight. Again, new high-strength, low-density non-metallic materials and composites are being developed for all parts of the engine to produce lightweight parts. Cases, rotors, shafting, and blades are all areas that are utilising advanced material and design concepts. Fewer stages in the fan, compressor, and turbine systems are major weight-reduction initiatives that are made possible by improved component aerodynamic efficiencies and stronger materials. Compression systems that develop higher pressure ratios per stage and turbines that extract more work per stage, are all tremendous contributors to engine weight reduction. The development of new designs to better mechanically "master" the thermodynamic behaviour of the engine cycle (e.g., the Variable Cycle Engine (VCE)) offers many advantages over the conventional "fixed" cycle. In order to fully exploit the advantages of the VCE, advancements in all areas of the triad shown in Figure 3 are required.

The continuing development and availability of radar and missile systems to non-NATO countries pose increased threats to NATO aircraft. The incorporation of low-observable technologies present a substantial challenge to both the operators and maintainers of NATO aircraft. The role of the engine in achieving low aircraft signature is large. Engine designers must continually employ advanced technology as they try to increase the stealth effectiveness, reduce the weight and complexity of the propulsion inlet and exhaust systems, and improve the robustness of low-signature surfaces. This area of advancement is fully dependent on the continuation of on-going programs in the engine technology programs of the future.

A third aircraft of the future, shown in Figure 6 as the "Global Reach Transport," needs an engine of high-bypass ratio (BPR of 5.0 or above). High-bypass ratio engines (in various thrust classes) are utilised for heavy transports, patrol/surveillance aircraft, long-range cruise missiles, and UAVs. The major issue of importance in these missions, in general, is low specific fuel consumption (SFC). Lower SFC provides improved range and time-on-station. The figure of merit to achieve low SFC is higher cycle pressure ratios combined with reduced weight. This is accomplished primarily through higher aerodynamic efficiencies in the fan and compressor engine sections, in conjunction with a reduced number of compression stages. The higher efficiencies are achieved through the use of higher rotational speeds and application of advanced computational fluid dynamic (CFD) codes that permit the optimisation of the flow through the compression section, minimising boundary layer losses and stagnation points. Other technologies include low-aspect ratio wide-chord blading, leading-edge sweep, casing treatments, and mixed-flow designs. In these types of compression systems,

weight is reduced through the use of "blisk" construction (blade and disk as one unit), hollow blades, fewer stages, and metal-matrix composite materials. Improvements in engine control system capacity, sensor data "throughput," and response time are now allowing compression systems to operate more efficiently in off-design regimes, and with lower stall margins. This translates to higher pressure ratios, safely, throughout the flight envelope, with lower weight.

For over 50 years, the gas turbine engine has used metallic alloys based in the nickel and titanium families. The properties of these material systems have been characterised and are well documented. Design standards and manufacturing techniques were developed, with high confidence levels, that high-quality hardware could be produced. The new, next generation of superalloys, intermetallics, and non-metallic systems is causing the gas turbine industries to establish new design standards, production processes, and repair/inspection techniques before incorporating them into the next generation of gas turbines.

With respect to these new, advanced material developments, a whole host of new metallic and non-metallic materials are being developed for specific uses in gas turbines. The environment in which these materials must operate is severe in terms of temperature levels and excursions and of dynamic stress fluctuations - the engine is murderous on materials! Therefore, extensive development and testing of new materials is required, to reduce the risk to acceptable levels before being incorporated into such a complex system as the gas turbine engine. Metal, organic, and ceramic-matrix composites, along with monolithic ceramics, titanium, and nickel aluminides, are all relatively new material systems that are being investigated for integration into many parts of the engine.

Other major issues associated with incorporating these advanced materials are: the ability to manufacture with a high yield rate; maintainability (reparability); durability (life levels); and understanding and controlling failure (wear and fracture mechanisms) while in use by the warfighter. This knowledge is fully covered by work in the "materials" leg of the triad shown in Figure 3.

For both the fighter and transport aircraft engines, improvements in the thrust/weight ratio (fighter priority) and low specific fuel consumption (transport priority) goals can be generally characterised as benefiting the following areas:

- Increased Propulsion System Thrust/Weight:
  - Higher Cycle Temperatures,
  - Improved Component Aerodynamic Efficiencies,
  - Advanced High-Temperature Materials,
  - Advanced, High-Strength, Low-Density Materials;
- Lower Specific Fuel Consumption:
  - Increased Pressure Ratio,
  - Improved Component Aerodynamic Efficiencies,
  - Reduced Cooling Flow and Leakage Flows,
  - Reduced Dry Pressure Loss for Augmented Engines,
  - In-flight Engine Performance Optimisation.

The advanced planning for propulsion has included all of the major engine component areas. Each area has specific, time-based goals to support overall engine system improvements. The magnitude and combination of these technology advances, applied to specific designs, vary depending upon the desires of the engine manufacturers and intended air vehicle system.

In terms of component technologies to support overall turbofan/turbojet improvements, all of the major component areas have specific goals, as listed below:

- Compression Systems:
  - Higher Aerodynamic Efficiency,
  - Improved Stage Loading,
  - Reduced Leakage,
  - Reduced Weight,
  - Higher Exit Temperature;
- Combustor/Augmentor Systems:
  - Higher Inlet Temperature,
  - Higher Exit Temperature,
  - Reduced Weight,
  - Improved Turndown Ratio,
  - Reduced Dry Pressure Loss for Augmented Engines;
- Turbine Systems:
  - Higher Operating Temperature,
  - Increased Work/Stage (Fewer Turbine Stages),

    - Higher Efficiency,
    - Reduced Weight,
    - Reduced Cooling Flow;
- Controls/Mechanical Systems:
    - Fibre-Optic Control Systems for Increased Data Throughput and Improved Electromagnetic Immunity,
    - On-line Performance Optimisation,
    - Integrated Flight/Engine Controls,
    - Magnetic Bearings/Ceramic Bearings,
    - Increased Lubricant Temperature,
    - Advanced Sensors and Actuators;
- Exhaust Systems:
    - Fixed-Area Designs (for Afterburning Engines),
    - Fluidic Exit Area Control,
    - Thrust Vectoring,
    - Airframe-Exhaust Nozzle Integration;
- Materials:
    - High-Temperature Titanium Alloys,
    - Titanium Aluminides,
    - Nickel Aluminides,
    - Metal-Matrix Composites,
    - Ceramic-Matrix Composites,
    - Organic-Matrix Composites,
    - Thermal-Barrier Coatings;
- Environmental Requirements:
    - Reduced NO_x,
    - Reduced Unburned Hydrocarbons,
    - No Visible Smoke Emissions.

Developments in these areas will result in improved aircraft and weapon system performance, combined with reduced maintenance events, and lower acquisition and LCC.

The development of integrated processes must be improved and shortened to reduce production costs and more rapidly take the product to the marketplace. These gains are also dependent upon advanced technologies, such as computer-aided design and manufacturing methods.

Turboprop/Turboshaft Propulsion Technology Needs

Turboprop/turboshaft engines are used in a variety of utility, attack, UAV, cargo, and surveillance aircraft. These applications include both fixed and rotary-wing aircraft. These aircraft operate primarily at low altitude, and cannot capitalise on the improved efficiency of operating at higher altitude. The recent Desert Storm experience revealed an operational need for increased payload and range for these aircraft, especially the rotary wing, and re-emphasised the need for efficient inlet erosion protection systems and lower signatures. The primary technologies that will provide these increases are those which lead to improvement in engine specific fuel consumption (SFC) and power-to-weight ratio (Hp/Wt).

Technologies that lead to improvements in SFC and Hp/Wt include the following:

- Reduced Engine SFC:
    - Increased Pressure Ratio and Operating Speed,
    - Improved Component Aerodynamic Efficiencies,
    - Reduced Cooling Flow and Reduced Internal Leakage,
    - Engine Performance Optimisation and Component Integration;
- Increased Propulsion System Hp/Wt:
    - Higher Cycle Temperature,
    - Reduced Cooling Flow and Reduced Internal Leakage,
    - Improved Component Aerodynamic Efficiencies,
    - Advanced, Low-Density, High-Temperature Materials,
    - Advanced Inlet Protection Systems,
    - Increased Turbine Rotor Speed.

The primary driver for increased range is reduced engine SFC. The cycle parameter which contributes most to reduced SFC is increased pressure ratio. The technologies critical to achieving increased pressure ratio, along with improved efficiency, are application of advanced CFD codes to optimise flow and minimise losses, along with advanced, high-strength, low-density materials which will allow the higher tip speeds required for higher pressure ratio compressors.

Other technologies which contribute include advanced controls to allow performance optimisation, advanced seals to minimise leakage, and advanced bearings to accommodate the higher rotational speeds.

The primary driver for increased Hp/Wt is higher cycle temperature. The technologies critical to achieving higher cycle temperature are:

- Advanced combustor designs to achieve higher exit temperatures while maintaining superior exit temperature distribution;
- The ability to operate smoothly over a broad range;
- Advanced materials and cooling techniques to maintain structural life;
- Advanced turbine designs with improved cooling techniques and advanced high-temperature materials to maintain and/or improve turbine life with minimum cooling air penalty.

Other technologies which contribute are advanced bearings and seals capable of operating at higher speeds and temperatures.

In terms of component technologies to support overall turboprop/turboshaft engine improvements, all of the major component areas have specific goals, as presented below:

- Compression Systems:
  - Higher Aerodynamic Efficiency,
  - Reduced Weight,
  - Higher Exit Temperature;
- Combustion Systems:
  - Higher Inlet Temperature,
  - Higher Exit Temperature,
  - Reduced Weight,
  - Improved Turndown Ratio;
- Turbine Systems:
  - Higher Operating Temperature,
  - Increased Work/Stage,
  - Higher Efficiency,
  - Reduced Weight,
  - Reduced Cooling Flow;
- Controls/Mechanical Systems:
  - Fibre-Optic Control Systems for Higher Data Throughput and Improved Electromagnetic Immunity,
  - On-line Performance Optimisation,
  - Integrated Engine/Flight Controls,
  - Magnetic Bearings/Ceramic Bearings,
  - Advanced Sensors and Actuators;
- Gearbox/Transmission Systems:
  - Reduced Weight,
  - Compact Design Concepts,
  - Hydraulic Design Concepts;
- Materials:
  - High-Temperature Titanium Alloys,
  - Titanium Aluminides,
  - Nickel Aluminides,
  - Metal-Matrix Composites,
  - Ceramic-Matrix Composites,
  - Organic-Matrix Composites,
  - Thermal Barrier Coatings.

Summary

Across the spectrum of NATO Nations, propulsion plans and programmes are in place to ensure that NATO's air superiority capability remains unaltered into the next century. The objectives are clear, the goals are achievable, and progress is being made. The turbine engine technologies emerging from the current programs will not only provide the necessary derivatives and growth of our currently fielded turbine engine systems, but also for the visionary systems for the future. In summary, the gas turbine engine presents many technical challenges, but the payoffs are worthy of sustained investment - without the engine, the aircraft becomes little more than a heavy glider. The propulsion technology development programs of IHPTET, ACME, and AMET are maturing the technology to effectively and efficiently power the NATO aviation forces of the future.

ANNEX 9: UNMANNED TACTICAL AIRCRAFT TECHNOLOGY REQUIREMENTS

Technology development will be critical to the development and deployment of the UTA system. It is important to note that a variety of technologies must be developed in parallel for integration, in order for the UTA to be a successful system. These technology developments include: control station and human operator interfaces, communications, sensors, data processing and fusion, aircraft design, and automated control.

Control Technologies

The control architecture for the UTA concept is a modular design to allow multiple control options for operational flexibility. The location of the control station (ground, air, or ship-based) and the degree of autonomy between the station and the air vehicle will be variable, to facilitate a general tactical air vehicle that can be adapted to accomplish a full range of missions. Variable autonomy and allocations of tasks will allow each control station to control more than one UTA, since the operator only has to focus on high-level mission functions.

An appreciation of the state transitions which will characterise UTA operations is shown in Figure 1. This is significant for control system technology requirements because of the different environments in which the system must function, ranging from runway operations and operations in controlled national airspace, through full combat operations. Each control function and the technologies which support its accomplishment must have the flexibility to adapt to these changing environments.

The functionality of the UTA control station will encompass many of the functions performed with today's tactical and reconnaissance aircraft - both manned and unmanned. This functionality can be broken out into four primary areas:

- Aircraft control, offensive and defensive operations, and weapons delivery;
- Communications;
- Mission planning and navigation;
- Intelligence.

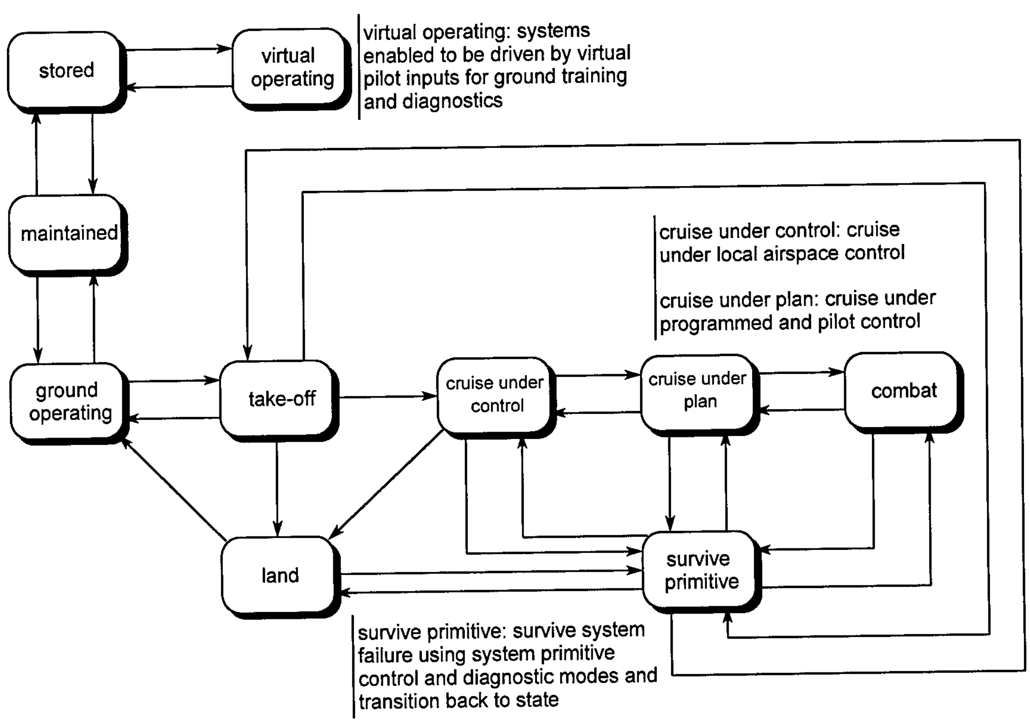


Figure 1: State Transitions for a UTA System

The first functionality area, basic aircraft control, is referred to as the core control station. The core control station is what is minimally required to operate a single UTA aircraft, with very limited aspects of the other areas of functionality. A view of control station functionality and modularity is shown in Figure 2. As additional UTAs are added and mission complexity increases, more stations would be added to handled the additional aircraft and influx of data. This control architecture will allow the system to be adaptable and flexible in order to meet a wide variety of mission requirements. This approach also allows the system to grow as new tactics and aircraft come into utilisation

It is envisioned that the control station have the capability to be either land, sea, or air-based. These diverse locations would require the control station to be modular in design, such that the "basic" control station, with enough functionality to be successfully easily integrated into a variety of platforms, while still maintaining the enough capability to complete its mission successfully. Control of any single UTA could then be passed between different entities for optimal mission configuration.

The key concept for controlling multiple UTAs with a single control station is variable autonomy. The control station would have the ability to autonomously control any system or mission function, in any phase of flight. The operator would allocate the control of tasks between the vehicle, control station and pilot, with the ability to adapt this control based on flight conditions and changing mission requirements. The ability of the operator to off-load tasking to automated systems will allow him to focus on higher level mission functions requiring human expertise, such as targeting, mission sequencing, target selection, weapons release consent, retargeting, compliance with the rules of engagement, and overall flight safety.

Because the UTA is lethal and will operate in cooperation with other tactical forces, the reliability of control is crucial. The system must achieve this reliability during communication link degradation and link loss. This suggests that the changing degree of control between the operator, the air vehicle, and the control station is not solely the operator's decision. There are situations where the system recognises that it can not allow high levels of operator control due to impeding conditions. In such situations, the control architecture must adjust the degree of operator and system control, then notify the operator of what it has done and conditions requiring this action. The conditions that create these situations, and the resulting actions, must be well defined within the system architecture.

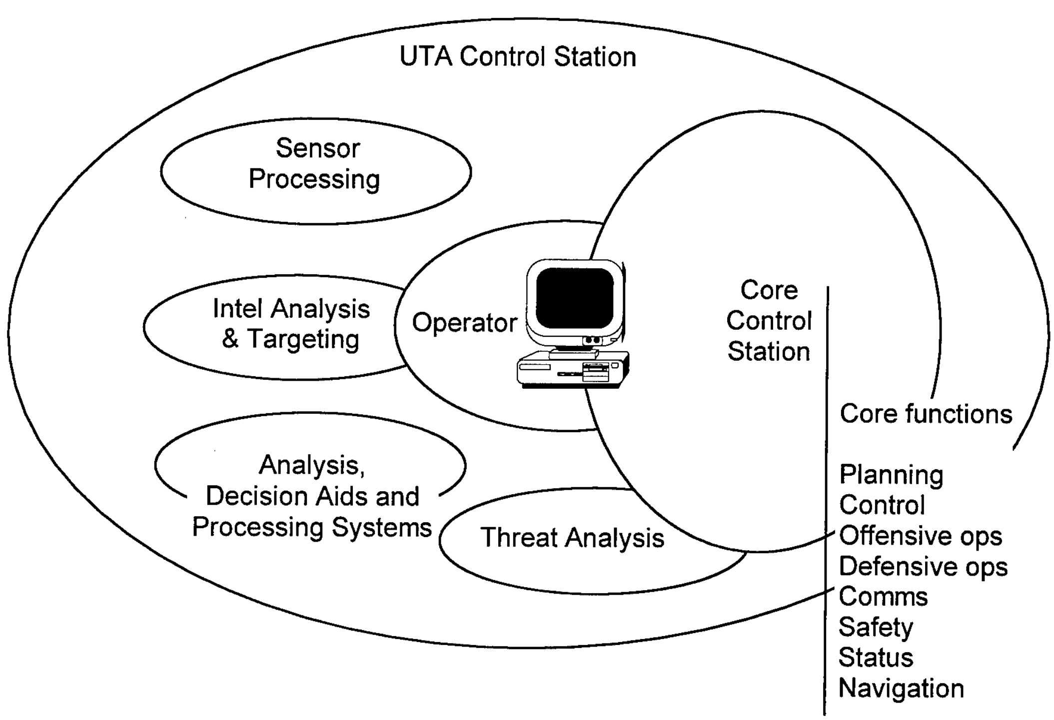


Figure 2: Control Station Modularity

There must be sufficient flexibility in the range of modes control for each function to reach to the dynamics in communications capacity, scenario conflict level, and environmental conditions. Before the mission, each operator must be able to tell the system how it intends to interact with it during the planned mission. The mission plan should include an initial event-based schedule, allocation of tasking, and division of control. During mission the operator will have a full range of control modes available to react to scenario contingencies.

Current UAV ground stations have been designed, for the most part, by image analysts with limited involvement from pilots. While this approach works well for UAVs performing reconnaissance missions, there are certain inherent limitations which must be overcome to fully exploit the UTA system. Current UAV control stations are designed to handle a very limited number of aircraft, and the UAVs which they control fly at high altitudes, at fairly slow speeds. The UTA system will possibly have several hundred aircraft flying at a variety of altitudes, at very high speeds, carrying weapons.

Because of these significant differences in operations requirements, the UTA system must employ radically new concepts for control stations. These concepts must exploit new and emerging technologies to allow the operator(s) to control/monitor the UTAs and make effective use of all the information and intelligence, without being completely overloaded with all the available data.

These technologies will include:

- Advanced high-resolution displays (high dynamic range, high-resolution colour),
- Wrap-around projection systems,
- Flat workstation displays,
- Advanced heads-up displays,
- 3-D High-resolution displays,
- Robust voice recognition and natural language processing; advanced databases,
- High-speed computing,
- Automated data fusion and correlation in real time, for very large amounts of data,
- The ability to selectively filter the data so as not to overload the pilot.

A summary of control station related technologies is shown in Table 1.

Communications Technologies

The communications requirements for the UTA go beyond the basic command and control. The concept requires downlinking of a variety of sensor data to the control station, interfacing the control station with intelligence assets so that real time mission planning/mission updates can be performed, and BDI/BDA dissemination of intelligence gathered during the UTA mission. For purposes of this Annex, the communications will be broken into two primary categories: communications internal to the UTA system; and communications external to the UTA system.

Technology Area	Application to Unmanned Tactical Aircraft
2-D and 3-D high-resolution displays	Control station situation display
Telepresence and virtual reality	Pilot interface for direct control and situation visualisation
Situation awareness decision aids	Multiple vehicle real-time tactical control tools
Natural language recognition	Pilot interface tools
Automated mission planning and routing	Multiple vehicle real-time control tools
Human factors	Pilot interface
Distributed interactive simulation	Training and rehearsal

Table 1: Control Station Technology Requirements

The goal of the UTA system is to have a seamless communications architecture which can pass data between the aircraft and the control station, through a variety of paths, to ensure a robust system that operates over extended ranges. These paths include Line-of-Site (LOS), SATCOM, and communications relay link. Each of these links must be compatible with the control station, either on the ground or in an airborne platform such as AWACS, ABCCC, JSTARS, and must be networked together for seamless connectivity. The basic idea of the communications relay link is to have each of the UTA aircraft act as a communications relay. This would allow the UTA to operate beyond line-of-site, without having to go through satellites, and also improve the robustness of the communications channel, such as in high-jamming environments.

In developing the communication requirements for the UTA system, a number of trade-offs must be made. These trade-offs are broken down into five primary areas:

- Channel capacity,
- Communications security and integrity,
- System integration,
- Co-site interference implications,
- Networks and data latency.

The trade space of most interest is the data capacity of the links. The communication system design should provide the highest data capacity possible, especially for the imaging sensors downlink, while maximising the LPI and AJ characteristics of the link. Security measures ranging from anti-jam to Low Probability of Intercept (LPI) are also of central importance to this system, especially for the Command and Control (C^2) link. This is due to the expected proximity of the aircraft to jammers on a typical mission.

Latency is another key component that comes into play, especially during the targeting and weapons delivery. While many aspects of the UTA mission can tolerate several seconds of time delay for transmission between the control station and the aircraft, other aspects can only tolerate tenths or hundredths of seconds delay. Closely tied with latency is the ability of the control station to control more than one aircraft, while not being overloaded by the influence of data from all the aircraft. The UTA system must be designed to handled these high-bandwidth bottlenecks without effecting overall mission performance.

While much of what has been discussed so far has dealt with UTA internal communications (between the control station and the aircraft), external communications are also critical to the UTA mission. The external communications capability provides a significant advantage over today's aircraft. By being able to provide the pilot in the control station access to essentially all pertinent intelligence and navigational data in real time, the UTA pilot will have significant advantages over today's pilots who have access to only a limited amount a real-time intelligence, due to narrow communication links and the amount of information which they can handle while flying the plane. The external communications will provide the capability for the receipt of intelligence data for mission planning/updating, dissemination of data interfacing with other military components for coordinated missions.

In order to have a robust UTA system, there are several technology areas which must be further developed. One of the core communication technology areas deals with networks. The UTA networked system must be able to automatically route data between all the aircraft, control station(s) and support assets, while being able to have dynamically bandwidth allocation (from several hundred bits to several million bits/sec), and to automatically prioritise data sets for aircraft that are in a combat state, for example. This prioritisation is important, due to the latency encountered in either networked or SATCOM links. Low Probability of Intercept (LPI) and Spread Spectrum (SS) waveforms are also key technology developments required. Conformal antenna research will also play an important role in the success of UTA, due to the increased manoeuvrability of the aircraft and need for Low Observables. A summary of communications technology requirements is shown in Table 2.

Sensor Technologies

The imaging sensors which are fielded on today's aircraft can be loosely put into two categories: reconnaissance and tactical sensors. Reconnaissance sensors are usually one of kind (or produced in very small quantities) that are extremely high-resolution and narrow field of view (FOV), and will often have some kind of line scan capability into order to increase the scan coverage. The tactical sensors are produced in

Technology Area	Application to Unmanned Tactical Aircraft
Spread spectrum AJ/LPI waveforms	Primary air-to-ground or air-to-air LOS data links
Intelligent high-dynamic bandwidth airborne networks, protocols	UTA airborne local area networks and data relays
Multiband multimode radios	Primary air-to-ground or air-to-air LOS data links and SATCOM data links
Agile beam conformal antennas	Data links and SATCOM for high manoeuvrability aircraft
Smart skins	Data links and SATCOM for high manoeuvrability aircraft
Smart push/Warrior pull decision aids and planning tools	Interface to theatre information environment and direct broadcast satellite data communications
Airborne network security	System security and command authentication; prevention of hostile exploitation

Table 2: Communications Technology Requirements

moderate quantities, have several FOVs in order to accommodate both targeting and navigational capability, and are designed to operate at much closer ranges than reconnaissance sensors.

The UTA will require not only the capability of current tactical aircraft (both targeting and navigation), but a new sensor capability, which is referred to as telepresence. The basic goal of this sensor capability is to provide a full 360-degree imaging sensor field-of-regard around the aircraft that could be transmitted to a control station. The basic idea of this sensor system is to distribute a number of small sensors (probably six) around the aircraft. The data from all the sensors would then be combined to form a single seamless image. This data could be used to provide awareness of the situation around the aircraft and could also be utilised in air-to-air combats.

An additional capability of this telepresence sensor system is to process the data onboard the aircraft, such that it would perform as an infra-red search and track (IRST). While this concept is not new, only very limited portions of the research and development and engineering have been done to actually implement this sensor capability in an aircraft.

A summary of sensor technology requirements is shown in Table 3 (following page).

Information Fusion Technologies

A virtual manned interface will inevitably be inferior to a real cockpit interface if the only information to be used in performing the mission is data developed by on-board aircraft sensors (which includes the pilot's visual out of cockpit sensor - the eye). Not all the data can be sent back over constrained communications channels, and there will always be some latency. For the virtual pilot of a UTA to be as effective - or more effective - than a real pilot in the cockpit, some other factor has to be present.

Locating the virtual control interface remote from the cockpit offers the opportunity to fuse many sources of information which can be made available on the ground but which generally cannot be sent to the cockpit. As the theatre integrated information environment expands, supported by backbone communications with ultra-high data rate (e.g., SONET/ATM land-lines and SATCOM links and the direct-broadcast Global Broadcast System) unprecedented amounts of archived and real-time information will be available on the theatre network. This can be exploited in its entirety by a virtual control interface, minimising the amounts of data which must be exchanged with the vehicle itself. This will be an important factor in making UTA

Technology Area	Application to Unmanned Tactical Aircraft
Distributed aperture imaging infra-red and electro-optical sensors	Wide FOV and high update rate tactical sensors (target detection, attack sensors, telepresence)
Detectors	Increased resolution and sensitivity
Focal plane arrays	Increased resolution and sensitivity
Uncooled detectors	Low-cost telepresence systems
Automatic target cueing/recognition	Target detection/recognition; subframe selection for transmission to remote human operator for analysis
Smart active skins	Active radar for highly manoeuvrable vehicles with dynamic geometry (SAR, RAR air-to-air)
Electronic scene stabilisation	Dynamic geometry compensation

Table 3: Sensor Technology Requirements

feasible and limiting the cost of its systems, particularly communications and sensor systems. A summary of information fusion technology requirements is shown in Table 4.

Data Compression Technologies

The goal of the UTA effort is to perform a significant portion of the sensor data processing (ATR) onboard the aircraft and disseminate only limited portions of the data to the decision makers. Consideration must also be given to the fact that some of the data that will be downlinked from the aircraft may be processed by other sources or just viewed by a photo-interpreter, each of which requires unique compression considerations. In the past, most compression algorithms have been developed with the human

Technology Area	Application to Unmanned Tactical Aircraft
Multispectral image fusion algorithms	Situation awareness, targeting, and attack
Intelligent filtering and correlation algorithms	Situation awareness, targeting, and attack
Automatic target cueing/recognition	Targeting
IFFN technologies	IFFN and “friendly fire” avoidance
Object oriented data bases	Data management and high-speed accession
Data accession search algorithms	Data management and high-speed accession
Application mediation technology	Accession of databases in arbitrary format by local applications
Targeting and target system analysis decision aids	Targeting, aimpoint selection

Table 4: Information Fusion Technology Requirements

Technology Area	Application to Unmanned Tactical Aircraft
Multispectral compression algorithms	Situation awareness, targeting, and attack
RT hardware implementations of adaptive multispectral algorithms	Situation awareness, targeting, and attack
Compression algorithms designed for both imaging and ATR processing	Targeting
Automated region of interest compression algorithms	IFFN and "friendly fire" avoidance

Table 5: Data Compression Technology Requirements

observer as the final user. This required the compression algorithm to focus on maintaining the low and mid-frequency components of the imagery, while throwing away the high-frequency components. Most ATRs operate on trying to find the edges of targets (i.e., the high-frequency components) which is just the opposite of many current compression algorithms.

Much work has been done in the area of sub-band decomposition (i.e., wavelets) compression, which overcomes the dilemma of having a variety of compression requirements. Sub-band decomposition allows for a very straightforward way to isolate the information in the image, in both the spatial and frequency domain, simultaneously.

To summarise, for the UTA effort there will be two primary compression issues for image data which must be addressed. The first is to be able to optimise compression for either a human operator or the ATR within a single band; second is to be able to optimise compression for multispectral data. All of this must be done in real time.

Other unique compression processing techniques will also be considered, such as Region of Interest (ROI) compression and progressive transmission. ROI compression is implemented by compressing a small portion of the image at a low ratio (e.g., 2:1) in order to maintain detail, while the rest of the image is compressed at a much higher ratio (> 40:1). This technique allows for much higher compression ratios, which results in faster transmission times while maintaining target detail and enough background information for situation awareness. A summary of compression technology requirements is shown in Table 5.

Airframe Technologies

An airframe which is built from scratch as a UTA will not be designed or built in the same way as a conventional tactical aircraft with the same general performance characteristics. This is a direct result of the life-cycle concept of operations and the elimination of the pilot from the system. This presents opportunities for innovative and affordable design concepts in a vehicle whose performance could be very high, compared to piloted designs. The opportunities will be significant, but will necessitate supporting technology development to enable an effective design.

Propulsion system technologies will be stressed by UTA in the event super-manoeuvrability is desired in the operational system. Current engines can sustain about 15 g's, based on the inherent strength of engine casings and mounts, and design of rotating equipment and fluid delivery systems. Lifetime at this acceleration level is likely to be limited. Technology developments will be needed to produce an engine which is sufficiently robust to enable the manoeuvrability of UTAs to reach maximum potential.

If super-manoeuvrability is required in the operational system of UTA, then this will have direct consequences upon propulsion system technologies. Normal piloted operation limits the actual g to less than 10. However, for unmanned operation, accelerations well in excess of 15 g can be anticipated. This will impose high transient incidence, which potentially could lead to intake stall or compressor surge as a result of high static or dynamic aerodynamic distortion. Appropriate attention must be given to avoiding this. High

acceleration rates will require strengthening of engine casings and mounts, as well as attention to turbomachinery and engine fuel system design. The prospect of a UTA flying beyond the flight envelope appropriate to a conventional aircraft must also be considered, which may extend the engine operating parameters, e.g., high altitudes and, hence, the increased risk of flame-out. Therefore, the impact of the overall UTA mission profile on the basic engine design cycle must be carefully considered. Furthermore, extending engine operating parameters could cause pressure margins designed into the engine casings to be exceeded. This possibility must also be identified and incorporated into the development programme.

High instantaneous or sustained manoeuvres about all axes will enable a UTA to be highly survivable in hostile environments, and to employ weapons in unique ways. It will also stress engine inlets, exhausts, and air handling systems and create difficulties in ensuring continuous operation of the engine at high thrust levels. The external and internal design of propulsion installations for highly manoeuvrable UTAs may be fundamentally different than that of conventional aircraft.

Innovations in structural design techniques and structural materials will be very important to the UTAs potential for reduced size, weight, and acquisition cost. A reduced flight hours lifetime will allow structures to be designed more for strength than for flexibility and tolerance to a high number of fatigue cycles. Aeroelastic effects may be much less significant for UTA than for conventional aircraft. Layout flexibility will allow new placement of aircraft systems and sub-systems. The structure for such an aircraft may be much simpler in design and manufacturability than conventional structure - for example, skin-stiffened composite primary structures with extensive use of foam cores. These technologies would lead to revolutionary decreases in airframe cost, but would require supporting developments - for example, all-electric aircraft systems with no hydraulics, avionics and sensor architectures without data buses, integrated as local-area networks, and providing the needed flexibility in locating components around the new structure and providing maintenance access in new ways, which reduce airframe costs.

Using a "fly-by-light" or other network oriented avionics architecture will likely be required by the UTA in order to achieve "wooden round" readiness. This kind of system, complemented by appropriate computing and software architectures, would allow the systems of aircraft in storage "baggies" to be accessed, exercised, diagnosed, and upgraded without removing the physical aircraft from storage. It would allow system component upgrades, over the lifetime of the aircraft, to be developed, integrated, and tested without requiring physical access to the aircraft - to be installed simply by plugging into the on-board net. Some of these technologies are currently under development, but more understanding, development, and testing will be needed to understand and fulfil UTA avionics requirements. This is likely to be critical to the ultimate success of the concept, since the high maintenance burden of avionics systems cannot be compatible with the basic rationale of the UTA. A summary of airframe and aircraft systems technology requirements is show in Table 6 (following page).

Aircraft Control Technologies

The goal of the UTA automated control system is to make the most effective use of all sources of information to effectively carry out the mission with limited user input. An overview of the automated control system data integration function is shown in Figure 3 (following page).

The automated control system will perform its operations based on a wide variety of data sets. These data sets will include data which is loaded on the automated control system processor prior to the UTA taking off. This data includes detailed mission planning/routing, digital maps and terrain data, intelligence information such as satellite images of collection areas or locations of known threats, priority targets, and alternative routing and target selection. Once airborne, the automated control system will utilise not only the data set loaded prior to take-off, but will exploit many additional data sources in real time. These additional sources will include not only the UTAs own sensor suite, but data from intelligence platforms such as Rivet Joint or new data (images, threats), sent either from a ground station or directly from reconnaissance aircraft such as the High Altitude Endurance Unmanned Aerial Vehicle (HAE UAV). While the system will have a pre-planned mission tasking, it will be designed to be as flexible and autonomous as

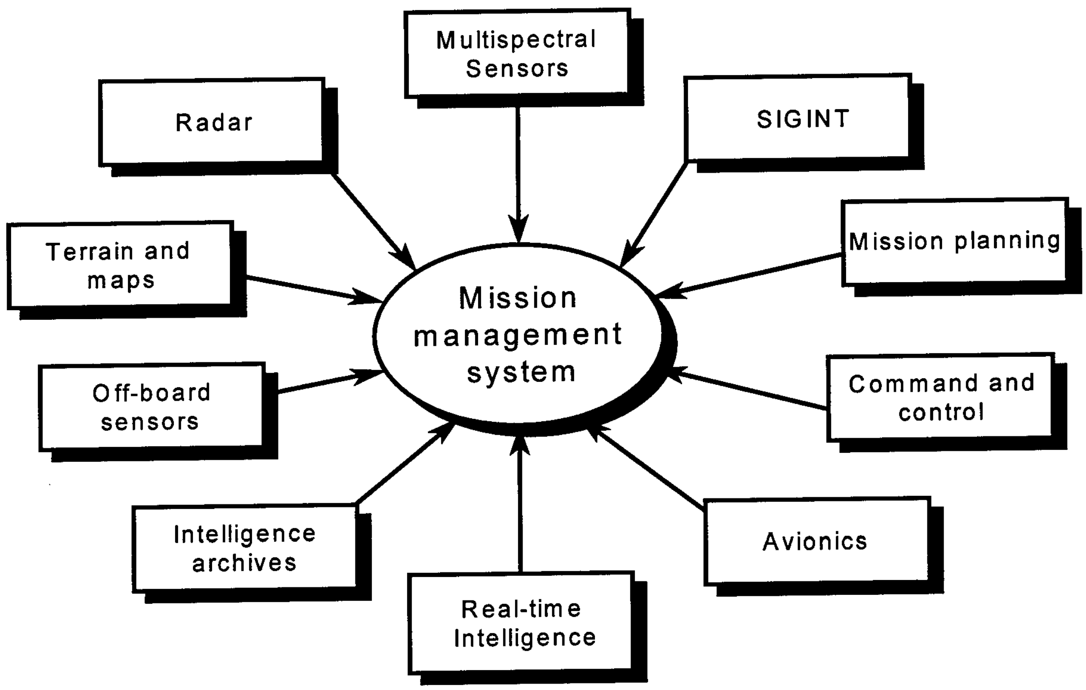


Figure 3: Automated Control Data Integration

Technology Area	Application to Unmanned Tactical Aircraft
Ultra-high manoeuvrability designs for turbine engines (casings, turbomachinery, flow systems, burners)	Propulsion for supermanoeuvrable airframe
Ultra-high manoeuvrability designs for inlets, turbomachinery, flow systems	Propulsion for supermanoeuvrable airframe
Composite Materials	Low-cost materials with properties tailored to UTA flight parameters and life-cycle concept of operations
Structural Design Techniques	Design methods for UTA flight parameters and life-cycle concept of operations, low-cost designs
Thrust Vectoring	All-axis control to replace aerodynamic control surfaces and high lift devices
Technology for replacement of hydraulics	Wooden round capability
Signatures technology materials	Survivability without on-board pilot situation awareness
Fly-by-light and networking avionics architectures	Avionics cost reduction, upgrade simplification, and compatibility with training and rehearsal by simulation

Table 6: Airframe and Aircraft System Technology Requirements

Pre-Mission Operation	Mission Operation
Digital maps	Planned weapon delivery
Digital terrain data	Updated target selection
Aircraft mission planning	Cross-cueing
Sensor collection planning	Off-board sensor fusion
Intelligence data	Real-time intelligence
Secondary routing	ATR/fusion processing
Collection planning coordination	Data storage
Airspace and communications coordination	Communications planning and control
Target priority list	Data dissemination
	Target and aimpoint selection
	Weapons release
	BDA

Figure 4: Autonomous Mission Management Operations

possible, as additional information becomes available during the mission, and to be able to deal the uncertainties that are inherent in tactical missions, such as unknown threats, aircraft malfunction or the loss of communication link. As mentioned above, the automated control system operations can be divided into two stages - pre-mission operations and mission operations. The system operations are listed in Figure 4.

Pre-Mission Operations. Pre-mission operations begin with detailed mission planning based the commander's air tasking orders and target selection. The target areas will include a priority list and a secondary list. The mission planning will include detailed routing to the target areas - both primary and secondary. This route planning will determine acceptable routes based on airspace coordination, possible threats, terrain, target locations, angle of approach to target areas, and targets. Also, alternative routes are planned as a back-up, in case the primary route is not able to be followed due to enemy aircraft, for example. There will be a series of alternative/backup routing plans to handle a wide variety of scenarios, including system failure and new targets of interest encountered during the mission. Additional data that is loaded onto the automated control system processor during this stage include: a priority list of targets and target locations; digital maps and terrain data; and pertinent intelligence data such as known threats, satellite or reconnaissance images of the collection areas.

Mission Operations. The UTA automated control system will be designed to handle the vast majority of mission operations, with little to no involvement from the pilot. The automated control system would be able to handle all aspects of the mission, including take-off/landing, navigation to pre-programmed routing to fixed target areas, and BDA. The automated control system will also be able to handle attacks from either surface-to-air (SAM) or air-to-air missiles by automatically taking the appropriate defensive tactical manoeuvre and employing the appropriate countermeasures, based on the type of threat. Another functionality that will truly make the UTA a superior aircraft will be the ability to either automatically detect and recognise (ATR) new targets with its own sensors, or to receive target reports and sampled image data from reconnaissance aircraft such as HAE. Based on predefined control logic, and if the new target is a higher priority, the UTA would cancel its current mission and search its on-board data base for an acceptable, predefined route that meets the pre-mission boundaries (airspace coordination, possible threats, and terrain data).

Automated Control System Technology Developments. The key technology areas for the automated control system can be grouped into three categories: detailed functional analysis and design, processors, and algorithms. The detailed functional analysis relates to being able to functionally break down every process of a mission in order that the algorithm for the automated control system can be implemented. While much of this work has been done, as can be seen in automated control in fielded aircraft (F-117 for example), a tremendous amount of work must be done to take into account the many dynamic functions described in this Annex.

In order to implement the automated control system, extremely high-speed processors must be used, such that the functionality of the automated control system can be implemented in real time. This is not considered to be a very high risk area given the current growth of processor technology and both government and private industry investment.

While all of these are currently very big research areas, much work must be done to have the automated control system functionality implemented in an aircraft. ATR continues to show encouraging results, but it is still not able to deal with a wide variety of backgrounds or camouflaged targets reliably. Data fusion and correlation processing also have shown results, but they are still limited to the fusion or correlation of similar data types.

An interesting method for which the UTA would be well-suited is to fuse a sub-sampled image of a target detection from a reconnaissance aircraft such as the HAE with its own sensor data, for target select or aim point refinement. The basic approach would be for an HAE to loiter over a target area for many hours searching for targets. Once a target was identified, an image of the target would be transmitted to a UTA in the area. The UTA would develop a routing plan to the target. Once in the target area, the UTA would begin to correlate its own sensor data with the data from the HAE for target detection or aim point refinement. This concept could also be used to pass image data from one UTA to another UTA in order to refine aim point selection for a specific target.

As stated before, much work has been done in image fusion, but there has been little success in a real-world dynamic environment. Technology requirements for on-board control are shown in Table 7.

Technology Area	Application to Unmanned Tactical Aircraft
Adaptive autonomy management	Management of adaptive autonomy for aircraft systems
Multispectral image fusion	On-board situation awareness for autonomous control
Multispectral ATR	On-board target and hazard identification
Miniaturised high-speed processors	Low-cost on-board processing for control
Intelligent filtering and correlation algorithms	On-board situation awareness for autonomous control
Intelligent planning and routing algorithms	On-board autonomous planning
Intelligent automated defensive manoeuvre planning and execution	Autonomous survivability; prevention of hostile exploitation

Table 7: Autonomous Control Technology Requirements

ANNEX 10: STRUCTURES AND MATERIALS FOR COST EFFECTIVENESS

Introduction

Advances in the technologies associated with structures and materials will be key to the ability to design, manufacture, operate, and sustain the aerospace weapons systems of the future. This annex focuses on improvements in five major areas:

- Multidisciplinary Optimum Design,
- Smart Structures Technology,
- Basic Materials,
- Manufacturing,
- Maintainability.

Multidisciplinary Optimum Design

The design and evaluation process can be a major cost contributor, both in capital and in time. It can be summarised as shown in Figure 1.

Traditionally, the multidisciplinary optimisation exercise has used empirical data or Intelligent Knowledge-Based Systems extensively to define the various derivatives and relationships between the state variables and the many constraints. The success of such optimisation depends on the accuracy of this data. An increasing number of these systems are being taken up by production and business-process modelling. Any knowledge-based system is only as accurate as past experience, so designs for radically new platforms are at risk.

However, the various sub-sets above are nearly all analysable numerically without empiricism, and the derivatives should therefore be ascertainable. This is certainly true in Structures, Systems, Electromagnetics and Acoustics, and (mostly) in Aerodynamics; and autonomous optimisation codes exist in these separate sub-sets. Because costs now have to be an integral part of the performance measures, estimates of the production costs of design components have to be part of the optimum design selection. A totally automatic system can therefore be imagined.

However, the immediate route forward is via Concurrent Engineering, whereby the tasks are performed by engineers in a semi-iterative fashion; and the outputs communicated both downstream and upstream, using a common network and data base. The constraints imposed by the performance (and cost) of the networks, computer hardware, and software tools, have largely disappeared. Whether a system is modelled for concurrent engineering and design,

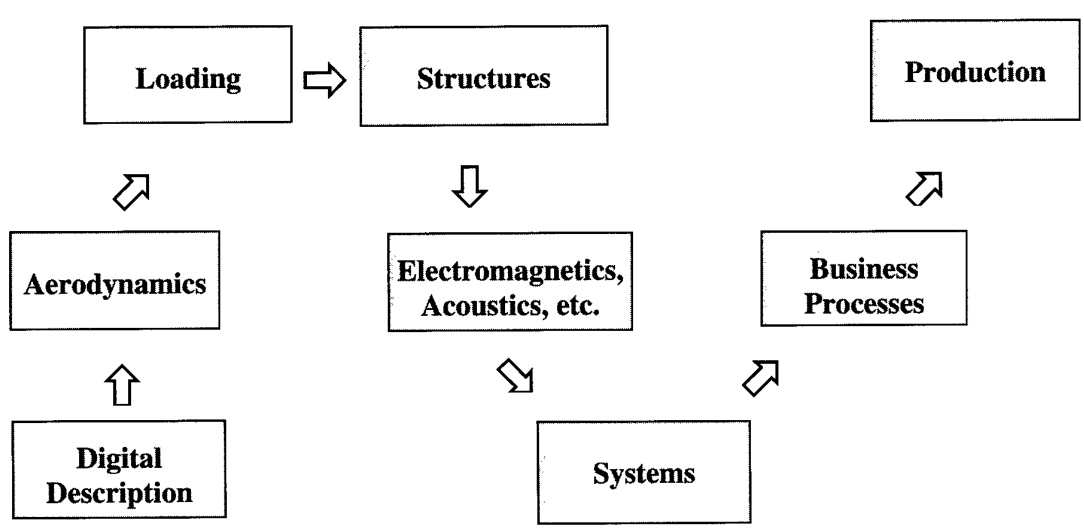


Figure 1: Design and Evaluation Process

or whether the optimum design becomes a truly automated process, it is clear that this synthetic model is a crucial part of the synthetic environment, and it will need to be accessible to departments of defence and the military services. The link between structural configuration and the planned manufacturing environment, when simulated, has come to be known as Virtual Manufacturing, or "an integrated synthetic manufacturing environment".

Smart Structures Technology

This is starting to show cost benefits. Distributed sensors and actuators open up the opportunity to apply distributed active control where conventional electro/hydraulic actuators have traditionally been used. Recent successes have been in isolating helicopter fuselages from blade passing noise, and now from high-frequency transmission whine, using magnetostrictive actuators. Smart structures have probably been oversold, and the transition from lab to full scale has proved difficult. The community is waiting for higher authority actuators. However, noise suppression has been achieved, because the amplitudes involved are small. General Electric has, for example, suppressed fan blade noise using distributed actuators around the internal surface of the nacelle intake. The missile bay supersonic cavity resonance could be solved in the same way, if it cannot be alleviated by aerodynamic tailoring. Tailplane or fin buffeting should be suppressible, or else the origins suppressed by smart vortex control. Acoustic panel fatigue is a prime candidate for smart suppression. Much more difficult than noise cancellation will be the smaller wavelength needed for boundary layer control. At the moment, blowing and suction seems the only route. Flutter suppression of controls and complete wings may be economic, but the durability of all smart sensors and actuators needs to be proved in the longer term.

Smart damping looks to be much lighter than passive, and to have a higher bandwidth. As mentioned, it should be possible to isolate all avionics and systems from all sources of vibration and shock, and hence enable cheaper non-mil standard equipment to be used.

Damage alleviation may eventually be possible for composite structures, using embedded distributed sensors/actuators which cancel damage-induced stress concentration. Smart (in-flight) repair may be possible using hollow fibres with embedded resin or by using thermoplastics and embedded heaters.

Adaptive meramorphic skins to change aerodynamic loading for control or trim are feasible, and should reduce drag or radar signatures. Again, the authority and the durability of the actuators, or the shape memory alloys, need to be proven. Smart or intelligent materials will also be deployed for non-structural reasons, such as optical and radar absorption control.

Basic Materials

Organic and metal matrix composites are in the forefront of high-performance materials, and a new initiative in fibres is needed for the 21st century. Research and development will continue on both carbon and ceramic fibres. Large-diameter, large-tow, coatable fibres that can be fabricated at low cost are needed. New affordable precursors and energy efficient fibre production processes will have to be aggressively pursued. High-volume, low-cost, ecologically benign processes for fibre production should be the primary focus. Modelling and simulation should yield specifications and designs, giving improvements in mechanical properties including specific strength and stiffness.

Research and development in low-cost, high-performance thermoset and thermoplastic resins is needed. The potential benefits of thermoplastics for recycling need to be exploited in the same way as in the automobile industry. Ecologically benign resins and processes need to be developed. Chemical companies are not motivated to invest in these areas for aerospace applications because of current low volumes, so new incentives need to be devised to stimulate work in this area. High-temperature resins are needed, as well as low-cost resins, for a broad range of moderate temperature applications, including resins for cryogenic fuel tanks.

New lightweight metals, which can be fabricated into finished products with low-cost processes, will be developed. Modelling and simulation tools to permit development of high-performance processable alloys should be a principal focus. Enhanced aluminium lithium alloys, for example, that could be made at lower cost, have improved durability, and be superplastically formed without

subsequent heat treatment, will find broad applicability. Lightweight alloying elements, such as lithium, beryllium, and magnesium, should be a focus, since density is a major driver in material selection. New aluminium, titanium, steel, and superalloys are needed.

Powder metallurgy and advanced ingot processing should both be included. Advanced solid-state joining of these new alloys should be developed to allow low-cost processing, such as superplastic forming/diffusion bonding of titanium.

Manufacturing

Studies need to be made to focus on materials and processes that are energy efficient and which minimise use of non-renewable resources, such as oil. This should be a major new science base study to guide our future in materials and structures. To date, very little has been done to thoroughly analyse (from basic raw materials to finished products) energy and resource consumption. Many thermal processes currently use very inefficient heating methods. This is acceptable today, due to the present low cost of oil; this situation is not certain to continue.

Automated thermoset and thermoplastic composite processing technologies for advanced aircraft and other applications need to be developed further. These technologies include:

- Fibre placement,
- Thermoforming,
- Diaphragm forming,
- Compression moulding,
- Injection moulding,
- Pultrusion,
- Resin transfer moulding,
- Automated ply lamination,
- Joining,
- Handling.

High-rate, automated fibre-placement technology is being developed for production of complex contoured structures. Work with complex woven preforms has included thermo-formed and pultruded structures, and has shown high potential for reduced material handling and low-cost processing. Various robotic techniques for fusion joining assemblies are being studied. Automation of the engineering side of composite processing, through the development of computer process models, and through integrating engineering, procurement, quality, and manufacturing, is vital to permit cycle time reduction, accurate cost prediction, and process improvements to produce high-quality, low-cost structural components. Automated fabrication and inspection equipment development is key to achieving cost and quality goals.

Efficient net shape manufacturing processes for metals and metal-matrix composites (MMC), like casting, spray casting, extrusion, forging, superplastic forming, powder metallurgy, et cetera, need to be developed for the new metals and MMCs discussed in the preceding section. Single-crystal engine blades have been a success story, but we need to widen this approach. The ability to "grow" a material to form a finished part that has tailored properties to meet varying functional and environmental requirements, using functionally gradient materials, needs to be exploited. Improved methods for manufacture of ceramic-matrix composites (CMC) and carbon-carbon, and efficient processes for coating large complex components need to be developed.

Advanced joining technology, such as diffusion bonding, laser and friction welding, et cetera, can be used to fabricate large, modular, cost-effective structures. Modular structural design can lead to much greater flexibility in design variants and development, to more use of "off-the-shelf" components at reduced costs, and to faster repair/replacement schemas. Such designs need not be heavily penalised by extra weight, if the advanced joining methods are successful.

Maintainability

The ability to rapidly perform Aircraft Battle Damage Repair (ABDR) is vital in combat. Battle-damaged aircraft must be repaired rapidly to allow their return to combat status. Maintenance personnel must be able to perform ABDR while wearing their Chemical/Biological Protective Ensemble, and with available forward base kits. Structural concepts and arrangements which minimise repairs required are obviously desirable. Extensive analytical and test work has been done on composite structures, including hydraulic ram effects on fuel cells, and design rules for spar spacing and stiffener attachment have been developed. New threats, such as larger, more powerful ammunition (30mm HEI, et cetera), laser weapons, and others, will have to be considered in the future.

PC-based, computer-aided repair design codes are available for ground engineers to evaluate the effect of battle damage to aircraft structure, and to design bolted or bonded composite repairs for the imposed strain field. The codes utilise a sub-structure approach and the full aircraft finite element model to permit rapid analysis on a PC, using condensed degree of freedom finite element cells. The use of local PC aids for design of repairs is likely to increase as aircraft age and multiple fatigue sites (some of which may have been repaired) become commonplace. It will not be acceptable for damaged aircraft to be returned to the primary manufacturer or for the manufacturer's help to be sought. Composite repairs to metal or composite structures will become smart. As a result, service engineers will be able to diagnose whether the repair is effective before take-off and during flight.

ANNEX 11: FUTURE DIRECTIONS IN ROCKET PROPULSION

The following narrative provides an insight as to where rocket propulsion must be advanced to support future air-launched missiles and space vehicles. The discussion is divided into four main technical themes: propellants, propellant management devices, combustion and energy conversion devices, and control systems. Within each theme, there is a discussion of boost and orbit transfer, spacecraft propulsion, and tactical propulsion.

Propellants

Boost and Orbit Transfer Propulsion

Current Space Lifter propellant systems consist of solid or liquid propellants. Although these technologies can be viewed as "mature," cost reductions, environmental improvements, and performance increases can be achieved by developing new ingredients, additives, formulations, improved processing, use of advanced high-performance thermodynamic cycles, and component design.

Solid Space-Launch Propellants: Due to the chemicals involved in solid propellant manufacturing, processing, and firing, solid propellants will be constrained by an increasing number of environmental regulations by the year 2000. Programmes to change the processes used in manufacturing and chemicals created during firing must be conducted to meet the regulatory challenge. In past efforts, performance has been sacrificed by replacement ingredients with less energy or lower density, in order to meet the environmental restrictions.

Development includes programmes to reduce or replace ammonium perchlorate (AP) to eliminate the HCL in the exhaust, and programmes to reduce or replace the aluminium powder as the fuel to decrease particulate emissions. The utilisation of commercially available energetic, non-halogenated oxidisers (ammonium nitrate and nitrate esters) are combined with high-energy, commercially available fuels and binders (e.g., magnesium aluminium alloys and polyether binders) to produce propellants capable of meeting these objectives.

Propellant developments to meet the solid propellant mechanical property objectives require an improved understanding and development capability of the internal mechanics of solid propellants (specifically binder-filler adhesion, particulate composite micromechanics, and fracture mechanics at the microstructural level). New binders and fillers also include finding corresponding bonding agents, catalysts, and additives that provide mechanical property control without compromising propellant performance. Approaches include improving and utilising modelling and simulation technology to predict the mechanical and chemical properties of the propellants and guide the formulation and processing of new propellants and propellant mixes. The resulting enhanced simulation of the propellant mechanical properties will allow the attainment of higher mass fraction and structural reliability of the propellant grains in solid rocket motors at significantly reduced testing costs, and increase safety by eliminating the need to formulate dangerous propellant mixes until a solution is determined. Other cost reductions will be realised through decreased processing time, by eliminating manufacturing steps, or using continuous mix cycles.

Liquid Propellants: Current state-of-the-art liquid systems are LOX/RP-1, LOX/LH2, and NTO/Hydrazines. The storable systems utilise the toxic nitrogen tetroxide (NTO) oxidiser, and hydrazine-based fuels. The LOX/RP-1 systems are less energetic than the LOX/LH2 systems, but they are also significantly less expensive in some applications. Non-toxic storable propellants need to be developed to meet the environmental requirements in the future.

Spacecraft Propulsion

Future satellite manoeuvring and on-orbit control requires improved reliability and operability to enhance satellite life span.

Propellants are sought for selected missions that offer life-cycle cost benefits through improved operability and/or reduced infrastructure requirements. Such propellants will be more benign and require less ground/flight support equipment than state-of-the-art, without

significant sacrifice of mission performance. Liquid propellant improvements in density impulse will be accomplished with respect to bi-propellant storable and mono-propellant storable systems. Non-toxic environmental approaches require assessments against programme issues (such as system uses) in new programmes. Programmes to achieve these improvements include research into synthetic fuels and hydrogen propellants that can be tailored to operational requirements. Additional critical activities will be directed toward improved ignition and manufacturing capabilities.

Tactical Propulsion

The wide range of missions for tactical systems require multifaceted technology applications to address the higher performance needs, with improved survivability and environmental compliance, at no compromise to cost or safety. Increasing propellant energy for the under 10,000 lb/sec total impulse motors, 10,000 - 75,000 lb/sec total impulse motors, over 75,000 lb/sec total impulse motors, gun-launched motors, and assist-boost motors requires development and application of new propellant ingredients (for smoky, reduced-smoke, and minimum-smoke propellants). These ingredients (fuels, oxidisers, and binder systems) will have to be of higher heats of formation and/or higher density. Near-term approaches include GAP, ADN, CL20, and perhaps, metallic hydrides. Propellants will have to be formulated to eliminate current burn-rate and combustion stability problems at pressures above 3,000 psi., and with greater strength than currently available to allow higher volumetric loading. In addition, tactical systems will no longer be limited to solid propulsion concepts. Liquid and, especially, gel propellants will be investigated for possible use. Tactical missile propellants being developed must be able to meet the insensitive munitions requirements. Significant reductions in the infra-red, ultraviolet, visible, and radar cross-section characteristics of the plume will be required to meet next generation tactical missile needs.

Propellant Management Devices

Propellant Management Devices (PMD) require technology improvements in hardware cost, support cost, reliability, and reduced component weights. This will be done by reducing the component weight, increasing the component reliability, and decreasing the individual component cost. PMD hardware for liquid rocket engines represents 35 - 40% of the weight and 35% - 40% of the cost of the entire liquid rocket engine system. This hardware includes:

- Liquid propellant turbopump assemblies (including pumps, turbines, housings, ducts, connectors, and insulation),
- High-pressure propellant and pressurant storage tanks (including expulsion hardware),
- Propellant tank pressurisation systems.

PMD hardware for solid rocket motors includes the motor case assemblies (both the case and insulation). The motor case and insulation are 43 - 70% of the motor inert weight, and 25 - 30% of the cost. The PMD technology area will pursue innovative sub-component and component design methods, manufacturing techniques, and materials appropriate for the respective component and application areas.

Boost and Orbit Transfer

Reusability has important implications in the design of liquid rocket engines, demanding more severe life requirements for the turbines, pumps, bearings, and dynamic seals compared to expendable engines. The primary technology challenges addressed in Phase I Boost and Orbit Transfer for liquid rocket engines are related to bearings, materials, flanges and connectors, and lines and ducting. The technological challenge for bearings is to survive a high rotational speed, with little lubrication. Implementation of fluid film bearings requires resolving issues of compressibility of cryogenic hydrogen, transient wear conditions, and fault tolerance. The support of hot, high oxygen content systems that are lightweight and reliable requires materials development. Robust structural materials will be developed for oxygen compatibility and for use of non-metallics in sub-components that typically only use metallics. To reduce assembly and replacement time, more easily operated, reliable, leak-free connector designs and seal materials are also required. Development of high-performance non-rubbing seals to separate incompatible fluids, e.g., liquid oxygen from hot hydrogen-rich gases, is also an important issue for the turbopumps of future liquid rocket engines. New manufacturing processes, such as powder metallurgy, should be

developed and qualified to improve performance and reduce the cost of high rotational speed components.

Improvements in case and insulation materials will address the challenges of reducing solid rocket motor weight. For solid rocket motors, the advancements that have the highest payoff are advancements of materials and a decrease in the variability of manufacturing. Improving insulation thermal performance per unit weight, while reducing the thickness required, will result in system weight and performance improvements. Decreasing the variability of the forming process can also decrease the weight by the reduction of the safety factors or, conversely, increase the reliability by maintaining the safety factors while improving the manufacturing process.

Spacecraft Propulsion

The issues for reducing the weight and cost of, and increasing the reliability of components for, spacecraft propulsion deal mainly with small cryogenic tanks and insulation. Cryogenic propellants offer major performance gains for upper stage orbit transfer; but they pose special challenges for satellite propulsion, due to cryogenic storage problems. Novel ground support concepts are required that will enable the low-cost management of cryogenic fluids during the loading and launch phases of the missions. In addition, lightweight, low boil-off cryogenic propellants in-space storage concepts are essential to fully realise the performance potential of cryogenic propellants.

Tactical Propulsion

In tactical propulsion, the motor case is the primary inert component affecting mass fraction improvement capabilities (for motors without TVC). In all tactical applications, higher strength to weight/volume case materials are required for higher pressure operation and greater propellant loading at reduced weight. Weight-constrained systems require high strength-to-weight materials, and volume constrained systems require high strength-to-volume materials. Volume-constrained systems tend to be less than 75,000 lb/sec total impulse (but these systems can also be weight constrained). The motors with less than 10,000 lb/sec total impulse are man-portable systems with volume and weight constraints. These systems have very poor mass fractions and will gain the most from the improvements.

Tactical motors in the 10,000 - 750,000 lb/sec total impulse, and over 75,000 lb/sec total impulse, can all experience significant performance improvements with better internal insulation. Internal insulation with lower erosion, lower density, and lower heat conductivity will allow less insulation to be used and more propellant to be loaded into the motor. Integral rocket ramjets (assist-boosters), in particular, can achieve significant performance gains, because the insulation must withstand extended ramjet operations as well as booster operation. Motors with less than 10,000 lb/sec total impulse rarely have internal insulation and would not benefit from insulation improvements. The insulation materials, case materials, case construction, and other components must be selected to meet the insensitive munitions requirements in order to produce a benign response to stimuli such as bullet impact, fuel fire, et cetera. Instrumented rocket motor cases will also become a practical proposition for in-service systems. These cases will make possible in-service data logging of the propellant grain's thermal and stress state history. This, in turn, will allow a much more informed appraisal of useful service life. Service users will wish to make use of this technology.

Combustion and Energy Conversion Devices

Combustion and energy conversion devices in the liquid chemical propulsion area include the thrust chamber assembly (ignitor, injector, combustion chamber, and nozzle,) and the gas generators or preburners. The major advances required in liquid propellant combustion devices include:

- An increase in theoretical Specific Impulse (Isp), by increasing chamber pressure,
- Increases in Isp efficiency, as measured By Isp actual/Isp theoretical,
- Reductions in weight,
- Reductions in cost,
- Increases in reliability (measured by decrease in part count).

The solid propulsion area consists of nozzles and the ignitor. In solid propulsion, the major advances required are in increasing Isp efficiency, decreasing component weight and volume, decreasing component cost, and increasing reliability.

Chemical spacecraft propulsion will require improved thrust chamber assemblies (similar to the improvements in boost and orbit transfer thrust chamber assemblies). Electric propulsion developments for satellites include the power processing components and the thrust chamber assembly, including the electrode. Major advances are needed in improving the power processing efficiency, the energy conversion efficiency, combustion chamber life, and electrode life.

Boost and Orbit Transfer Propulsion

The thrust chamber assembly represents an average 32% of the overall cost of a boost or orbit transfer engine. Current manufacturing techniques rely heavily on expensive forging, machining, welding, and brazing processes that require large amounts of touch labour. Development efforts should concentrate on the significant reductions in cost and component lead-time that will be realised by incorporating advanced design and fabrication techniques into the next generation engine. Examples of this include the use of cast structural jackets to replace the current forged and welded structure, and diffusion bonding non-precision cooling tubes to replace the brazing of precision stacked tubes. Injector costs can be reduced through lowering the number of injector elements, eliminating expensive welds and brazes; or through the use of advanced techniques, such as laser drilling and platelet technology, to manufacture injector elements. Solid rocket motor nozzle cost will be reduced by decreasing the processing time and number of steps.

The thrust chamber assembly represents an average of 41% of the mass of a liquid rocket engine. In order to increase the thrust-to-weight ratio of the propulsion system, this mass must be reduced. The usage of advanced composite materials to replace structural metal jacket should result in the largest weight reductions possible on the engine. Passive radiation-cooled nozzle extensions further enhance the weight reductions through the use of lightweight composite materials. Reusability has important implications in the design of liquid rocket engines, demanding more severe life requirements for the thrust chambers, nozzles, preburners, and/or gas generators.

In order to achieve significant increases in liquid propulsion Isp, the chamber pressure of a liquid rocket engine must be increased. Current materials are limited by a combination of temperature capability and thermal conductivity. Increases in either of these parameters will increase the pressure capability of the thrust chamber, without the need for efficiency robbing propellant film cooling.

Current engine designs are optimised for maximum performance at only one specific altitude, hurting performance at all other altitudes. Delivered Isp can be improved by either improving the combustion (c*) efficiency of the combustion chamber, or through the use of altitude compensation in the expansion nozzle. Current technology fixed-bell nozzles are optimised for maximum performance at only one fixed altitude. Operation at any altitude other than the design point results in a performance loss. Altitude compensation, either through the use of translating, ventilated, or dual-contoured bell - or "non-conventional" concepts such as aerospike nozzle - will allow liquid engines to operate at near-optimum performance throughout the flight trajectory.

On solid rocket motor nozzles, the delivered Isp can be improved by decreasing the nozzle throat's erosion rate. An increase in nozzle throat area creates an accompanying decrease in area ratio. This is counterproductive to performance, especially in the case of space booster motors, where an increase in area ratio with increasing altitude is desired. Composite materials with higher temperature capability and oxidation resistance are required to maintain throat geometry.

Improvements in c* efficiency will be sought for LOX/RP-1 engines through design improvements in the injector. Current efficiencies are from 90 - 94%. Improvements in vaporisation and mixing will enable increases to the range of 96 - 98%. Combustion stability must be maintained with this increase in performance.

For the ignitor component of liquid engines, methods of increasing reliability and supportability will be developed. Current bi-propellant torch ignitors require individual propellant lines and associated valving to function.

Solid rocket motor ignitors are commonly initiated with electromechanical arm/fire devices requiring a complex explosive ordnance train. Electro-optic arm/fire devices that incorporate a laser diode through a fibre-optic transmission

cable have the potential for lower weight, reduced cost, and higher reliability.

Spacecraft Propulsion

In chemical systems for satellite propulsion, the major challenges are cost, Isp efficiency, and volume. Because these systems are generally radiation-cooled, Isp efficiency gains will be achieved through the development of higher temperature capable materials and new technologies. New techniques for applying coatings to extend the chamber's temperature capability will be explored. Concepts to reduce the dimensions of satellite propulsion systems are also required for volume-constrained satellites or launchers. High-pressure pump (or pressure) fed systems may offer 50% volume reductions and improved performance. Cost savings will come from the same composite manufacturing techniques that apply to the space launch application components.

Satellite propulsion of nonchemical means includes electric propulsion, solar propulsion, and nuclear propulsion. In electric propulsion, the current technology is a specific impulse of 520 seconds, an energy conversion efficiency of about 33%, operating lifetime of 800 hours, and a power processing efficiency of approximately 90%.

Improvements in arcjet systems are required in order to reduce mass, extend life, and reduce power requirements. Significant increases in satellite lifetime can be obtained by increasing the arcjet specific impulse and energy conversion efficiency. The approach to improving these parameters includes the reduction of frozen-flow losses and/or the reduction of power deposited into the arcjet body. The arc in the arcjet is notorious for squandering up to 50% of the input power into the non-recoverable internal energy modes (frozen-flow losses) of the propellant (e.g., ionisation and dissociation). As service life of satellites is extended, the operational life of the arcjet must also extend. For high-power arcjets, the major issue is the cathode life. Technology needs to be developed to extend the lifetime up to 2,500 hours. Pulsed plasma thrusters, hall thrusters, and ion thrusters are other possible solutions to meet the increasing demands placed on satellites. Hall-type thrusters offer a performance advantage over Arcjet thrusters in some thrust classes. Development work on the components, to reduce size and increase efficiency, will be carried out.

Pulsed-Plasma Thrusters are able to operate in thrust ranges below those ranges in which other electric propulsion systems can operate. Component improvement programmes will be run to improve performance, and to reduce weight and volume.

A new class of propulsion system is Solar Thermal Propulsion. Work needs to be accomplished in developing the concentrator and thrusters.

Tactical Propulsion

All tactical motors can benefit from reduced erosion nozzles. Incorporation of low-cost carbon-carbon materials or refractory metals may have significant benefit. Tactical motors in the 10,000 - 75,000 lb/sec total impulse, over 75,000 lb/sec total impulse, assist boosters, and divert categories can be operated at altitudes from sea-level to over 100,000 ft altitude.

Altitude-compensating nozzles (such as an aerospike) need to be developed to provide optimum expansion ratio at varying altitudes, which can provide increases in delivered energy in excess of 3% and an additional 5% increase in motor performance. These nozzles must be designed to be minimum weight/volume system, to avoid loss in propellant loading when compared to current nozzle designs. Motors with less than 10,000 lb/sec impulse usually operate near sea-level, thus altitude compensating nozzles would have little or no impact. There will also be a need for thermo-structural materials, allowing simple low-cost nozzle designs for tactical motors.

Control Systems

Technology advances are required for control components to reduce propulsion system hardware cost, reduce support cost, increase thrust-to-weight, increase mass fraction, and reduce failure rates. Application of innovative sub-component and component materials, manufacturing processes, and design methods and approaches appropriate for the respective component application area will be pursued.

Different types of application-driven propulsion systems (liquid, solid, et cetera) use vastly different control system components.

Technology areas consists of the following components:

- Liquid engine health management (includes sensors, controllers, and control software),
- Valves and regulators,
- Solid motor and liquid engine thrust vector control (TVC) actuators,
- Solid rocket hot-gas valves.

Boost and Orbit Transfer Propulsion

Decreasing the weight, power requirements, and costs of liquid engine valves is achieved through reduced-torque valve designs (making electrical mechanical actuation possible) incorporating advanced materials and low-friction seat materials. Improvements in materials, processes, and design techniques allow for the use of integrated multifunction valves.

Highly reliable propulsion system health management sensors and controllers are required for propulsion status monitoring and life-cycle surveillance. Sensors of interest include flow, temperature, pressure, rotational speed, position sensors, and accelerometers. Developing more reliable sensors with non-intrusive measuring techniques is desired. When intrusive methods can not be avoided, new sensor designs and fastening techniques will be developed (especially for reusable systems). Fault-tolerant control logic, with a minimum number of sensors required for prudent status monitoring, is essential to guard against sensor failure-induced engine shutdowns. Validation of optical and magnetic sensors being used for health management systems will also be completed. Furthermore, maintainability and health monitoring become important aspects to be taken into account during design and development of a reusable system.

Similar to liquid engines, current TVC systems for solid rocket boosters are heavy and expensive. Electrohydraulic or pneumohydraulic systems are used where lower actuation forces are required. Current TVC actuators are large as well; they have historically been hydraulic, due to the requirement for large actuator force and high slew rates and vector angles.

For solid motors, the simplest TVC concept is the hot-gas injection system, where the combustion gases are bled from the combustion chamber and fed through a hot-gas valve into the nozzle and exit cone to cause flow separation and to effect thrust vector offset. The limitation for this concept has been a lack of materials capable of withstanding high combustion gas temperatures and combustion products.

Spacecraft Propulsion

Liquid propellants pose unique challenges for satellite propulsion systems. These propulsion systems, while required to operate for long lifetimes (over 10 years), must be highly reliable, in addition to meeting restrictive weight goals. Frequently, component designs are compromised to meet the restrictions. For example, valves and regulators are being deleted from system designs in order to save weight (despite the seemingly trivial weight they add). This compromise is suspected of causing some satellite failures, due to the lack of adequate propulsion system control. Satellites will also benefit from more reliable, fault-tolerant health management systems similar to what is being developed for space launch propulsion applications.

Tactical Propulsion

For tactical propulsion, control systems need to include improvements in thrust vectoring, thrust modulation, and actuation technologies. These efforts must include capabilities to handle liquid and gel propellants, as well as traditional solid propulsion pulse motors and thrust vectoring. Tactical gel, and liquid propellant systems require low-cost, low-weight, low-volume valves and regulators for propellant pressurisation and feed systems. Chemical compatibility, sealing, and safety will be the primary problems in this research. Tactical motors in the 10,000 - 75,000 lb/sec total impulse, over 75,000 lb/sec total impulse, assist boosters, and divert categories will all experience significant performance improvements with better control systems technology. Improvements in the thrust vector control system include reductions in system mass, by the development of high specific strength materials with good thermal and erosion resistance. Reductions in cost, by using integrated low parts count designs using thermo-structural materials, are required. Thrust modulation for solid propellant motors is a technology goal with particularly high systems benefits, combining the ruggedness and low cost of solid systems with the flexibility of liquid propellant systems.

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14. Abstract

Volume II, the main volume, of the report of the NATO Advisory Group for Aerospace Research and Development (AGARD) study: 'Aerospace 2020'. This study explored the most advanced technologies, relevant to aerospace, being researched and developed in laboratories today. The study focused on the most promising current technologies and the organisational and tactical consequences they will have at the field and system levels, over the course of the next 25 years.

Topics include: a discussion of the impact of proliferation, human-machine interaction, synthetic environments, directed-energy weapons, information technologies, unmanned tactical aircraft, suborbital launchers, hypersonic missiles, and a discussion of affordability issues.

Technologies are assessed from the viewpoints of both potential capabilities and threats. Observations and recommendations are presented.

Volume III contains technical papers in support of the conclusions reached. Volume I is a short summary of the conclusions.

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